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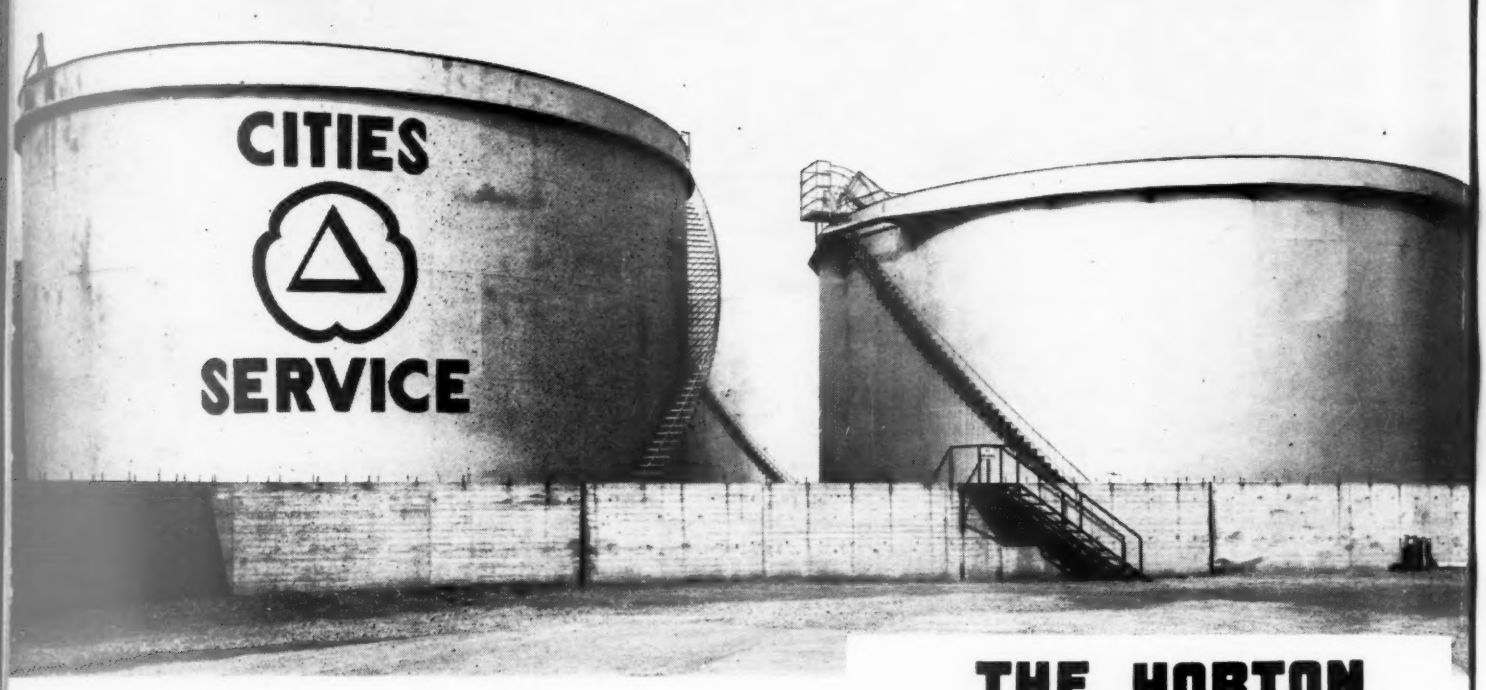

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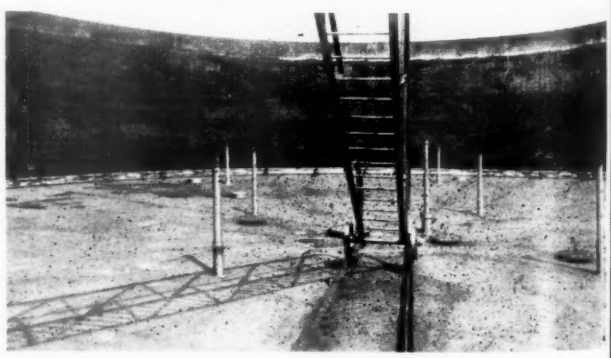

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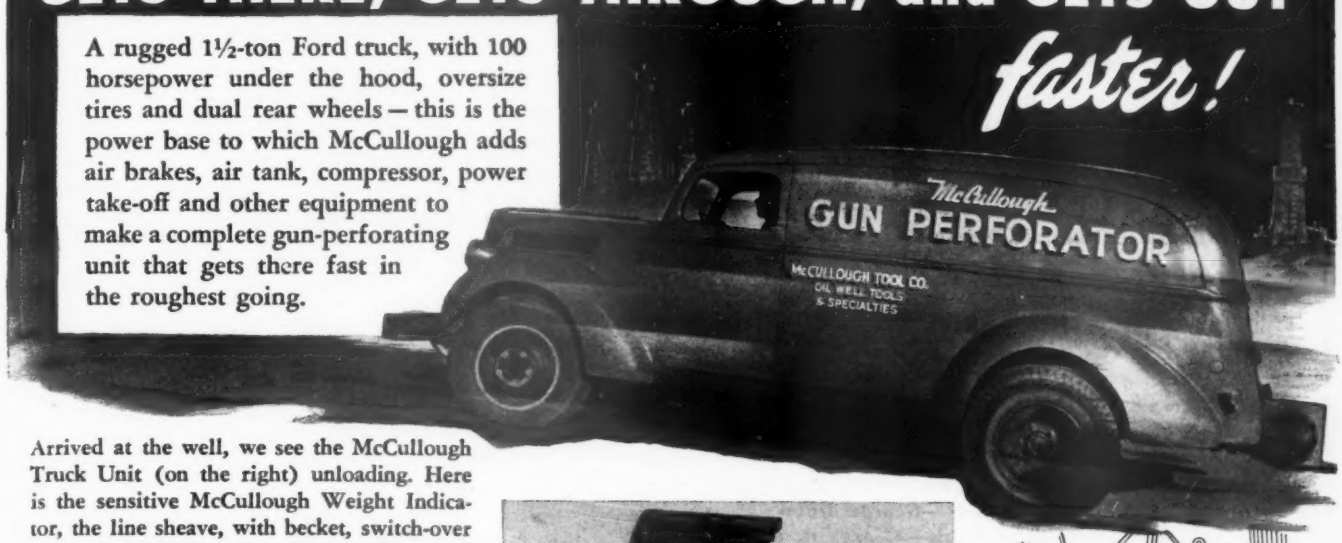
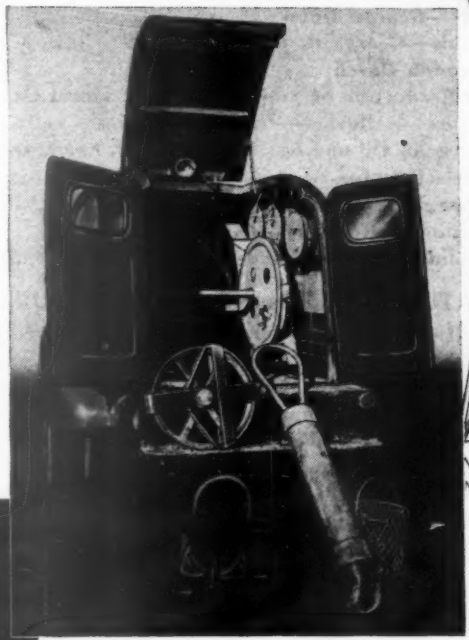
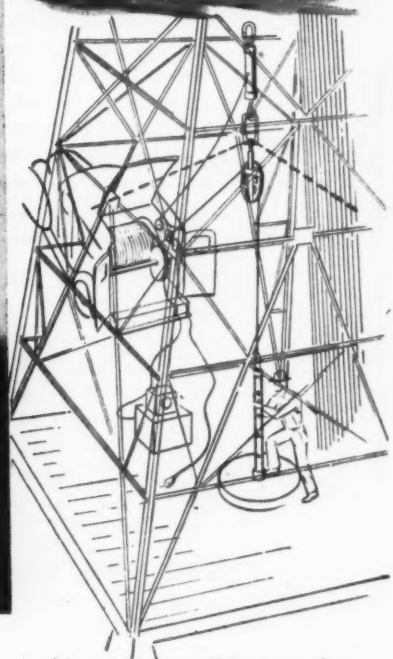


Arrived at the well, we see the McCullough Truck Unit (on the right) unloading. Here is the sensitive McCullough Weight Indicator, the line sheave, with becket, switch-over nipple and "Oil-Saver" packing head (a small blowout-preventer). In the truck, you see the line reel and measuring sheave, and the reels of cords for electrical connection to the rig. Overhead is a spotlight for night operation.





Below is the operator in the truck, his hand on the brake that controls the line travel, as he watches the shock-mounted instrument panel. This panel contains a two-way loud speaker, sonic indicator switch, line testing plug, multiple-stage weight indicator, line speed indicator, depthometer, line-testing switch, volt-ohmmeter, and combination shooting switches —the latter so arranged that the gun cannot be fired accidentally.

The sketch at the right shows the complete, quickly-made hookup as the gun starts down the well—electrical connections made to the weight indicator, the loud-speaker and shooting switch. All these connections have different type plugs, making it impossible to make a wrong hook-up. To render accidental shooting absolutely impossible, the gun cannot be fired unless the man on the rig holds down *his* shooting switch at the same time as the truck operator presses his *two* switches.

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VOLUME XVIII NUMBER 10

REFERENCE ANNUAL

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New Feature

Comprehensive bibliography of important papers for year 1946-47.

Classified by division in petroleum industry.

Described by name of paper and author, by meeting where given, place and date.

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Editorial

THE POST-WAR demand for petroleum products far exceeds the most optimistic estimates. It is the greatest in the history of the industry and is constantly increasing.

To meet this unprecedented upturn in demand and also to insure being able to fill future needs of the nation and the public, "during 1947 alone American oil companies are investing nearly two billion dollars." Operating divisions of the industry thus have heavy schedules to meet.

Present oil reserves are being drawn upon almost to capacity. In an effort to find new reserves, exploration work is witnessing the greatest activity in its history.

Wildcatting is greater than it has been for several years, yet is not adequate in view of the increasing demand for petroleum.

Construction of new plants and revamping of old ones are under way in the refining industry.

Many new methods and practices are in the making looking toward increasing efficiency and effecting economies. It is significant that companies are making vast expenditures on new research facilities, and that these facilities are not confined to any one division, but cover every phase of operations.

Disturbing factors are the continuing dislocations, arising from the war, that still harass the industry. Shortages of certain steel products is one of these, and has greatly retarded drilling operations. Pipe line construction has also been adversely affected and several projects have been held in abeyance.

The years immediately ahead promise to be a period of great activity and new developments in the oil industry. The task of keeping abreast of things will be increased. In this connection, progress in the operating divisions of the industry being reflected in the papers presented before technical societies, trade associations, and other related groups, a selected list of such papers, valuable for reference, is contained in this issue. As an added service to aid readers in keeping informed on operating practices, this issue also contains a complete bibliography of important papers published during the last twelve months.

The Reference Annual is a special number, not one of the monthly issues, and therefore does not carry the regular features. The contents are selected papers of significance that have been presented during the previous year.

Recent trends in geological-geophysical exploration and methods of improving use of geophysical data*

By R. CLARE COFFIN, Stanolind Oil and Gas Company

● **Abstract.** Since 1942 the use of gravimetric methods has increased in the United States approximately 200 per cent, seismic methods 50 per cent, core drilling 100 per cent, and the magnetic investigations 70 per cent. The impact upon geological thinking because of this continued increase of geophysical effort is discussed. Full advantage offered by these methods and combinations of methods is not being made. A better use of the low-cost methods is pointed out. With the tremendous increase in the use of the gravity method there has not been a corresponding improvement in the proper understanding of its possible use and its limitations. The gravity method is discussed in some detail. A tremendous improvement in our geological thinking and a better use of geophysical data are possible by an education of "district" or "grass-root" geologists in geophysical concepts and a freer use of this information. A trend in this direction is noted, but the need of an accelerated move in this trend is emphasized.

● **Introduction.** The geological staffs of oil companies were so depleted during the war that a minimum of work was devoted to the development of new geological ideas. The need of reserves was never greater and extra effort was put forth to make new discoveries; but this special effort included not new procedures but a greatly increased use of existing techniques, with expenditures in geophysical exploration greatly increased, as the following figures show.

Approximately 150 gravity meters were in operation on oil exploration in the United States in November, 1945, an increase of 200 per cent over the activity of 1942. During this same period the seismic units increased to 324 (a 50 per cent rise), core drills to 52 units (a 100 per cent increase), and magnetic exploration 18 units (a 70 per cent increase). In fact, the geophysical exploration in some areas was limited only by avialable men and equipment. A noticeable decrease in geophysical exploration is recorded in the first three months of 1946, but this exploration effort probably will remain at approximately its present high level through the present year.

In passing, it is of interest to record that similar exploration increased tremendously in Mexico and South America during a similar period. Three service companies offering seismic and gravimetric exploration in foreign lands offer an index to this increased activity. This group alone reported a total of three seismic units and one gravity-meter unit in operation in Mexico and South America in 1942, and 21 seismic units and 10 gravity meters operating in 1945. This activity represents approximately 30 per cent of the geophysical exploration being conducted in these countries.

The development of an air-borne magnetometer for war purposes and its adaptation to general magnetic mapping is a revolutionary advance. The use of such equipment will stimulate magnetic exploration generally and make feasible the investigation of areas not accessible by ordinary means of travel.

Other geophysical activity at the beginning of 1946 includes four companies offering soil-gas analysis and one analyzing the fluorescence of soil samples as a means of exploring for petroleum direct. At least two companies report the use of electrical methods during the period.

Although there were few new developments in geological methods during this period, some progress can be reported in the application of old techniques to new problems. The renewed interest in the Rocky Mountain states brought many geologists to this province to do surface mapping and thus restore an art all but lost to our profession. The use of insoluble residues in the pre-Permian beds of West Texas has been successful in breaking down the Ellenburger formation into several recognizable units. Improved methods of logging shallow core holes by electrical methods have made core drilling feasible in areas that formerly could not be economically explored because of the lack of recognizable shallow markers. New logging services include new procedures and improvements in the quality of data provided by established methods. Gamma-ray logging has become an accepted practice in some areas. A method of determining dips in drilling wells by electrical methods was perfected and made available to the industry in 1943 and radioactive bullet markers used in 1944 assisted geologists in making precise the location of pay sands in deep wells. Seismic and gravity methods were adapted to work in the open ocean during the war period, and exploration of parts of the Gulf of Mexico is now under way.

Studies neglected in recent years in-

*Presented before American Association of Petroleum Geologists, Chicago, Illinois, April 4 1946. Published in *AAPG Bulletin*, Vol. 30, No. 12, December, 1946.

clude the origin of sands, analysis of waters, and studies of temperature gradients. The geologist who undertakes any of these special studies finds himself at a disadvantage because of the lack of material in the provinces best suited for investigation. The question then arises as to the limits we should go beyond those generally imposed on a drilling well to obtain data on all formations drilled. Every wildcat well is a research project and within certain limits should be so treated. The idea suggests itself that some cooperative scheme be initiated whereby information be obtained from all wells drilled within a selected area and thus provide data from numerous strata, making possible exhaustive geological research. The problem invites discussion not possible in this paper.

An examination of our geological and geophysical expenditures will focus attention on that part of our exploration effort that is of maximum concern. The exploration budgets of at least three companies whose geological and geophysical expense exceeds $5,000,000 yearly carry items for geophysical expense in excess of total geological expense in ratios ranging between 5 to 1 and 10 to 1. Obviously, the geophysical expenditures that have continually increased for the last 10 years will remain, and properly so, at a high level indefinitely.

Analyzing the result of this tremendous effort in acquiring new data of use to the geologist, we should have cause to wonder how exhaustively this information is being used. Little, if any, geophysical data can be analyzed to the point where the original interpretation can be made, conclusions drawn, and the geophysical records put aside. The problem becomes stupendous when we realize that almost any well drilled necessitates a reconsideration and a re-study of the original data; in fact, the geophysical data in some areas require a certain amount of exploration by drilling before an intelligent interpretation can be made.

The purpose of this paper is to inquire into certain phases of the progress of geological thinking during this period in which geophysical expenditures have grown to such high levels. Have we been sufficiently alert to the advantages offered by the tremendous acceleration in the rate of supplying data to the geologist? From such an analysis we see the need of a definite trend in geological procedure and thinking to maintain a well balanced exploration program.

We have been continually asking for an exploration method by which to explore for petroleum direct. Certain methods working to this end have not yet reached the stage where they are satisfactory. Until a direct method completely satisfactory is developed, the geologist is challenged to make better use of the things now at his command.

At the risk of being considered out of place in presenting these ideas before a geological group, rather than before a geophysical group, and at the risk of being considered elementary, the writer presents certain phases of geological-geophysical thinking that may seem trite but which, however, are fundamental. Such a repetition will attempt to prove that the geologist must have a better understanding of geophysical concepts if he is to make better use of existing information.

To project geological interpretation beyond the initial and apparently obvious interpretations made by the geophysicist at the completion of this original work involves geological thinking of the highest order. To construct a map from the initial seismic data, or to draw circles on gravity maps outlining anomalies, is only the beginning of geophysical interpretation. The geological aspects of only

FIG. 1-A. Gravity contours of area in West Texas; contour interval 0.5 milligal. Anomalies at A and B produced largely by density contrasts between redbeds and limestone at depth of approximately 4000 ft. Both the anomalies outline known structures.

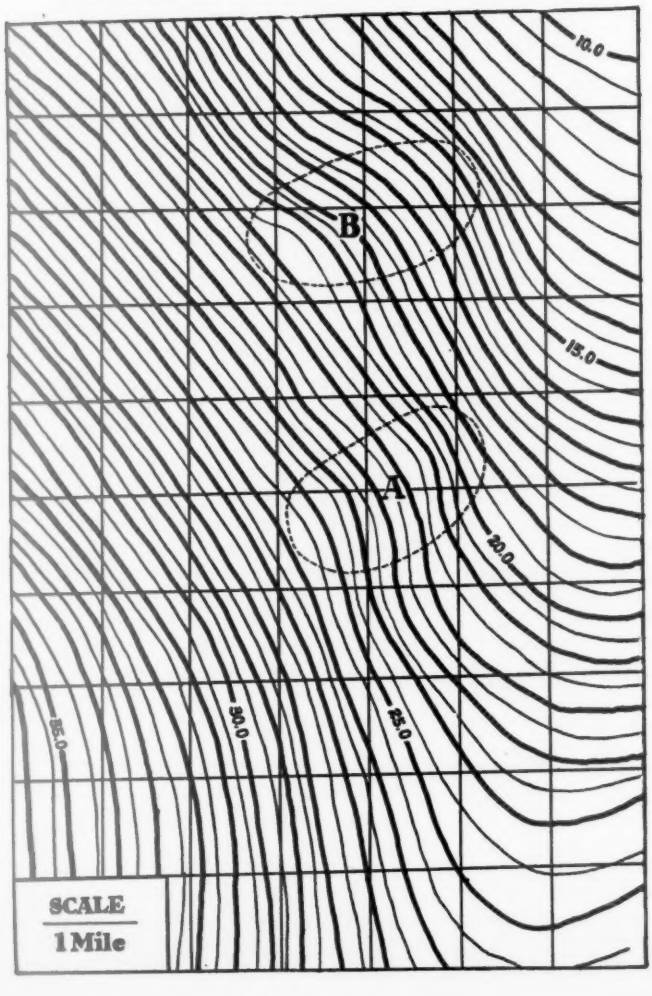
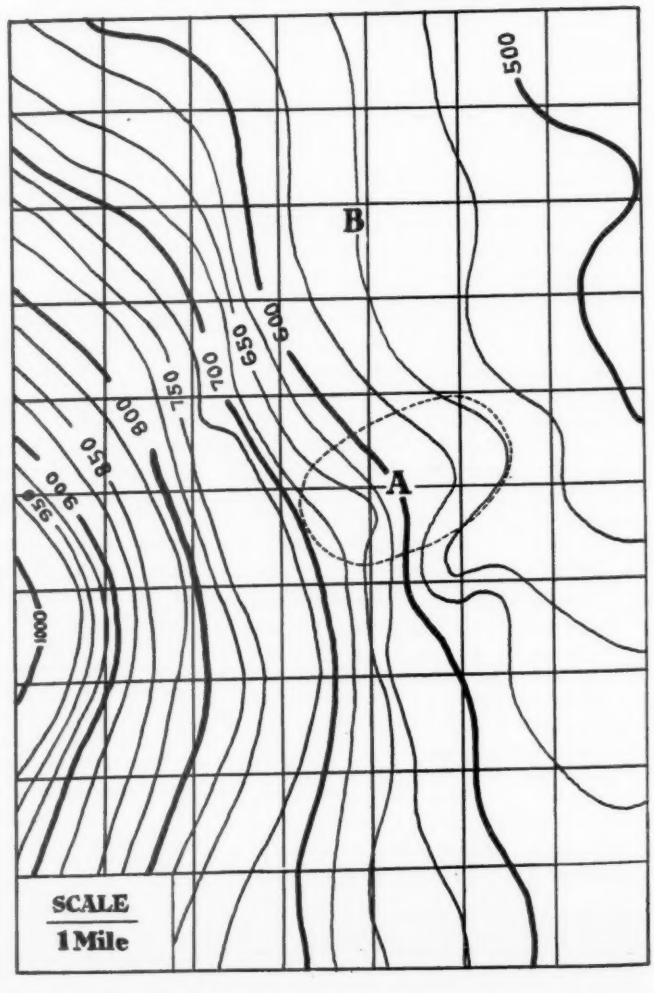


FIG. 1-B. Magnetic contours of area in West Texas; outlined in Fig. 1-A. Contour interval, 25 gammas. Note magnetic anomaly at A and absence of any at B. Pre-Cambrian formation that produces this anomaly is known to be 3000 ft deeper at B than at A.



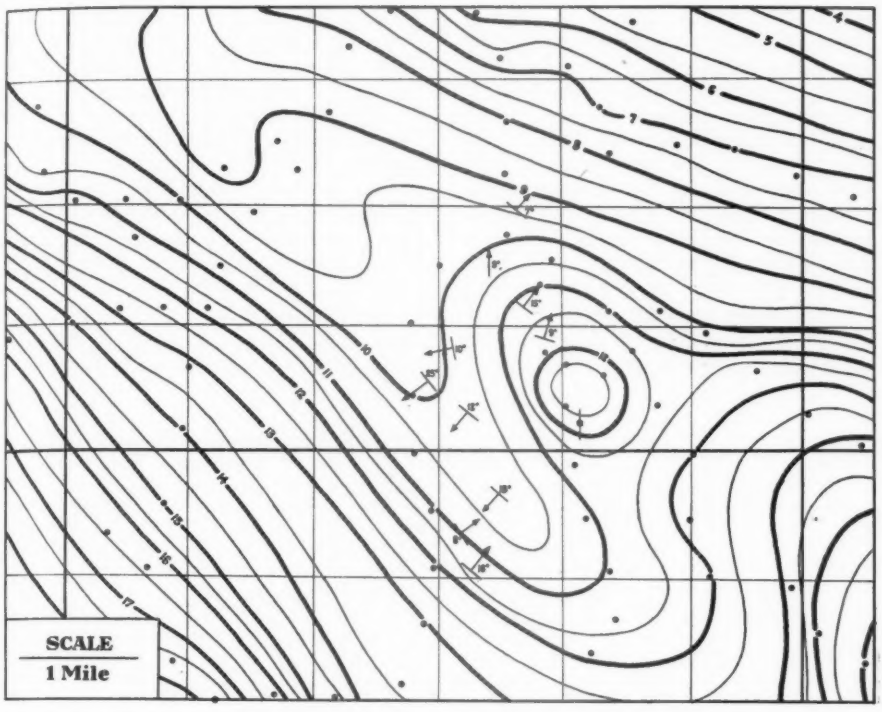


FIG. 2. Gravity anomaly in Tertiary-covered area of Rocky Mountains; contour interval, 0.5 milligal. Area characterized by pre-Tertiary structure and topography either of which might produce anomaly. Dips from limited seismic exploration confirm presence of shallow structure rather than pre-Tertiary topography.

those phases of geophysical-geological interpretation which have not received their proper attention will be discussed.

● **Coordination of geophysical exploration.** No geophysical surveys employing the commonly used devices fail to contribute data by which the geology of an area may be better understood. The question may be asked, "Does the information contribute enough to be worth the cost of obtaining it?"

Any contemplated program of geophysical exploration involving one or more methods must be based on the general approximation that a gravity survey costs per unit area ten times that of a magnetic survey, and a seismic survey ten times that of a gravity survey. The cost of core drilling ranges so much that no figure can be given that would be meaningful in this cost schedule. In general, it is more expensive per unit area explored than other methods and should be used only in special cases where other methods have failed.

If the geophysical characteristics of an area lend themselves to exploration by low cost methods, a progressive order of work from the less expensive to the more costly can be used with distinct advantage in the ultimate cost of the work. Frequently a consideration of more importance than the ultimate cost is the timing of the exploration effort and the speed with which information is made available by the low cost methods. The question of which technique is best suited for any given area may require a trial, but within certain limits the effectiveness of some methods can be predicted; this will be discussed later.

Rightly used, a series of geophysical surveys from the less costly to the more costly will progressively narrow the area of interest. Under such a program the value of any one survey is difficult, if not impossible, to determine — all combine in producing a finished product.

The writer takes violent exception to the thought implied in many analyses of exploratory effort, wherein a series of discoveries is listed and the methods responsible for each discovery. If these analyses reflect accurately the methods employed, it is evident that the geologist frequently is not using the several geophysical techniques in proper coordination. Under ideal conditions the several methods should not be used competitively but each should contribute an essential part in the program. A simple statement of an actual case serves to illustrate the point.

A magnetically anomalous trend supported by a limited gravity survey provided the incentive in leasing a 50,000-acre block so far ahead of the exploration for the area that the cost per acre was one-fifth the going price for wildcat acreage being paid in neighboring counties. Core drilling followed in two selected areas in the block. In one area a map of a shallow marker was sufficiently interesting to justify a well, which discovered a new field. An anomalous picture was obtained in the second area by core drilling. A limited amount of seismic work was then completed, a second well located, and a second field discovered.

The area involved parts of Barton County, Kansas, and the two pools discovered were the Richardson and South Ellinwood. The original cost of the block was 10 cents per acre and the overall time from the beginning of the work to the time when the second prospect was ready for drilling was one year. The records mention that one pool was discovered by core drilling and the second by seismic methods — what an injustice to the exploration effort!

The fact that additional oil pools have been since discovered in the area covered by the original surveys but not predicted by the original work does not detract from the methods or from the coordination employed. The original discoveries provide the geological characteristics of the area and the focal points from which further exploration could be planned in an orderly manner at a minimum expense.

The simultaneous interpretation of two or more sets of geophysical data has many obvious advantages. Special advantages of such a procedure are found in areas where the data from any one method are inferior in grade, or the results inconclusive. In making interpretations of several sets of data, it is vital to have well in mind the probable geological circumstances responsible for each. Under such conditions two sets of geophysical data can be made to complement each other.

Magnetic and gravity exploration in West Texas and adjoining New Mexico are both effective, but for different reasons. The magnetic disturbances are related to the structural features of pre-Cambrian rocks, and the local gravity anomalies are due largely to the density contrasts between the redbeds section and its associated salt with the "lime" below—two horizons that may be several thousand feet apart.

The mapping of the surface formations is justified even where the information itself does not have impressive significance, but when taken with an adequate gravity survey may be of much value. A single isolated outcrop of pre-Tertiary beds in the Tertiary-covered areas of the Rocky Mountains may be of inestimable value in helping in the interpretation of a regional gravity map. A few strategically placed core holes, or a single seismic traverse of limited extent with a regional gravity survey may serve the same purpose of predicting the general structural picture which can be further explored in an orderly and well planned manner with a minimum of expense.

In dealing with several sets of geophysical data, each inadequate in itself to provide a solution to the problem, the geologist is faced with the same problem confronting a doctor in diagnosing an ailment. Two different symptoms are many times more valuable in drawing the proper conclusion than one, and three are better than two. The sum total of the value of these clues may not be an algebraic sum but some larger value.

A series of marginal seismograph traverses obtained in an area where salt domes are expected may be combined with an inconclusive gravity survey to suggest whether or not a salt intrusion is to be expected. Again, a marginal seismic survey can often be combined with a marginal gravity survey to change

an area of questionable value into one having a third- or second-class rating which demands further exploration.

Many instances have been noted where complete gravity surveys have outlined the presence of deep-seated features that the original seismic exploartion failed to find because of inadequate exploration. Under such conditions special effort and special techniques should be employed to give proper attention to the area. Let us examine two areas where two or more sets of data can be used to the mutual benefit of both methods.

The outlining of two gravity anomalies in Fig. 1-A is clearly justified at points *A* and *B*. Subsequent exploration has shown both to be structurally of interest. A magnetic map (Fig. 1-B) of the same area outlines a magnetic anomaly at *A* but none at *B*. Inasmuch as structure of the limestone strata at 4000 ft is responsible for the gravity anomalies and the pre-Cambrian formations are responsible for the magnetic effects, it follows that the pre-Cambrian is much deeper under structure *B* and at *A*. This conclusion has been confirmed by drilling which places the pre-Cambrian more than 3000 ft deeper at *B* than at *A*.

A prominent gravity anomaly in a Tertiary-covered area is outlined in Fig. 2. The area is characterized by much pre-Tertiary topography which permits the possibility that the gravity meter mapped only topography. A few well placed seismic dips eliminate this possibility. Again, the shape of the gravity anomaly indicates the beds providing the density contrasts are shallow. The feature was explored by a core drill hole less than 2500 ft deep.

● **Gravity surveys and their interpretation.** The unprecedented increase in the use of the gravity meter in the last

FIG. 3-A. Structure of Shoshone and Cody anticlines, Park County, Wyoming, Contours on top of Cloverly group. Interval 500 ft.

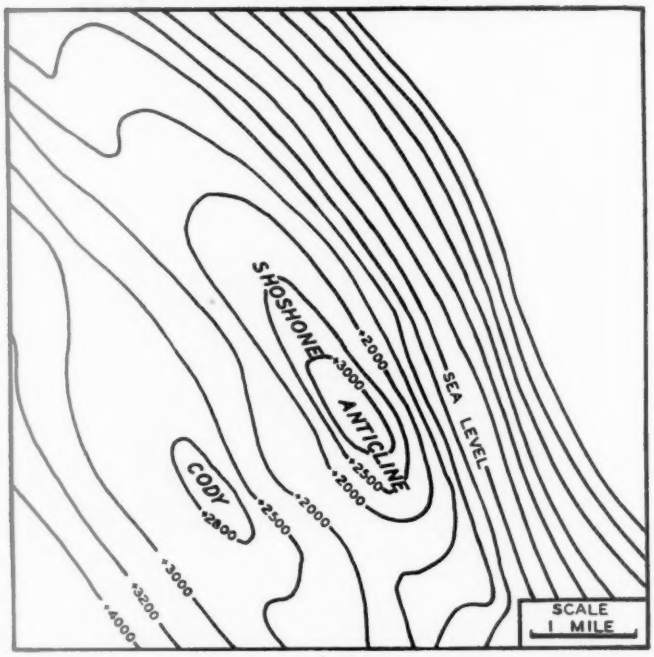


FIG. 3-B. Gravity anomaly computed from structure outlined in Fig. 3-A. Contour interval, 0.5 milligal. Heavy lines outline position of structures.

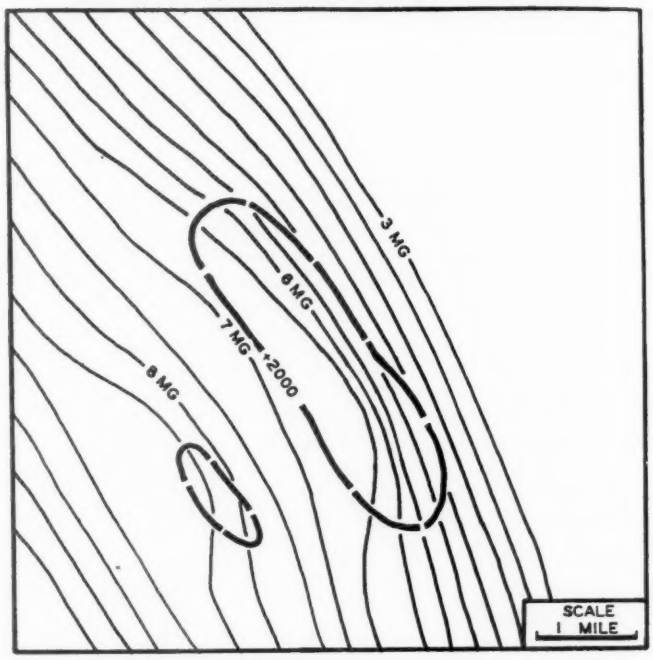


FIG. 3-C. Gravity anomaly of Fig. 3-B with regional gradient added.

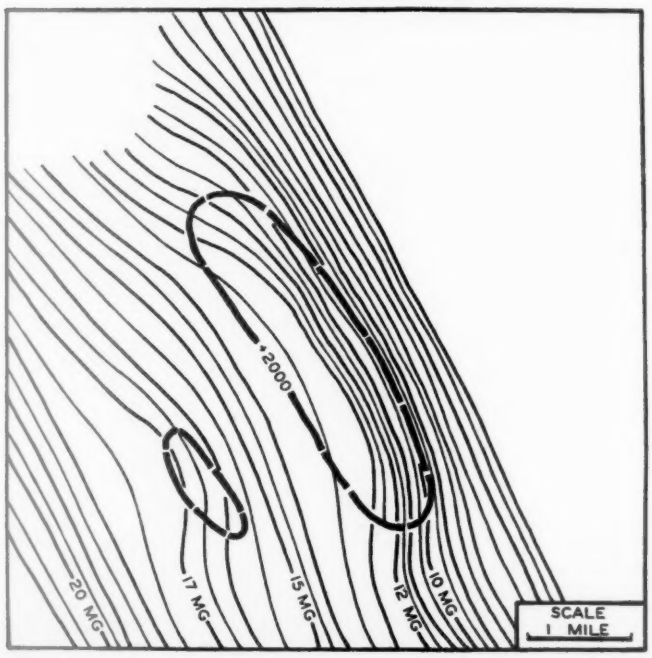
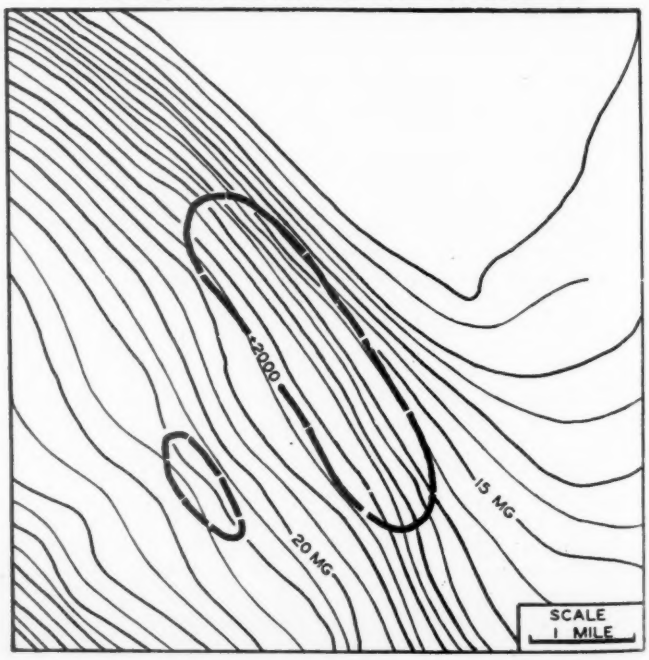


FIG. 3-D. Observed gravity of structures outlined in Fig. 3-A. Agreement between Fig. 3-C and D is fair. Inaccuracy in original structural map may account for some of these differences.



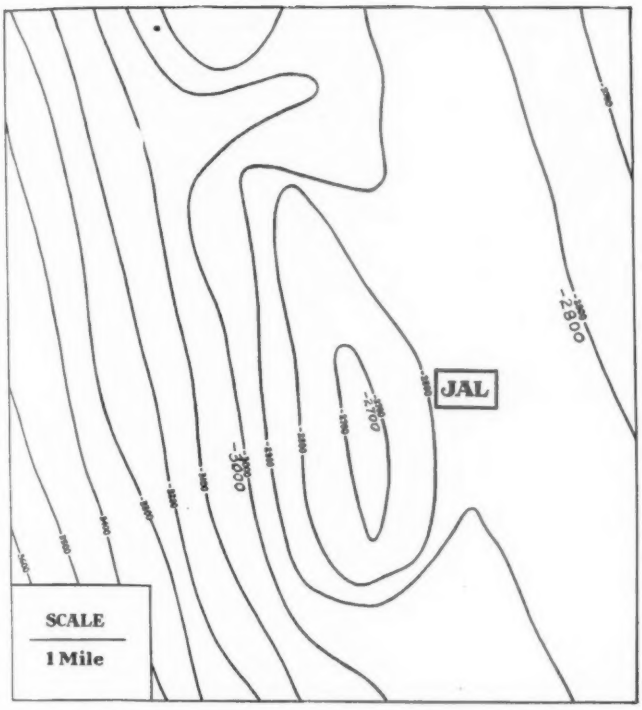


FIG. 4-A. Structure on top of San Andres in vicinity of Jal, Lea County, New Mexico.

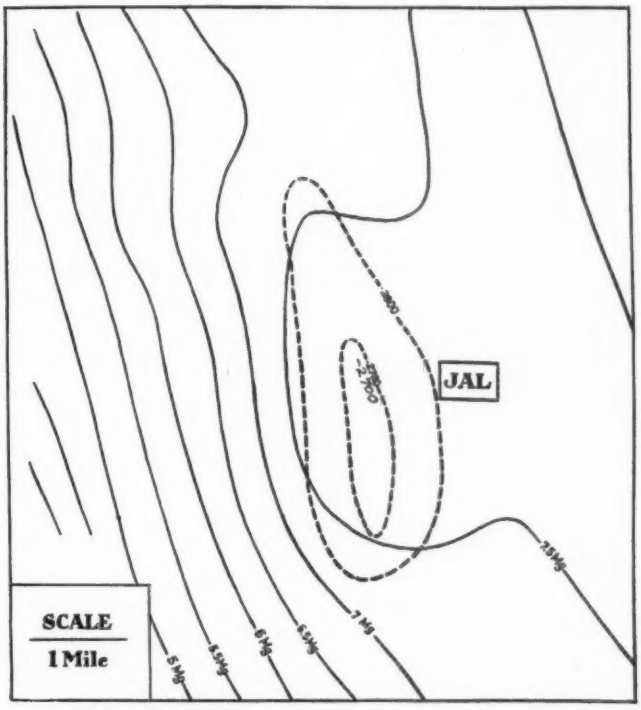


FIG. 4-B. Gravity anomaly computed from structure of Fig. 4-A. Contour interval, 0.5 milligal. Dashed lines from San Andres structure.

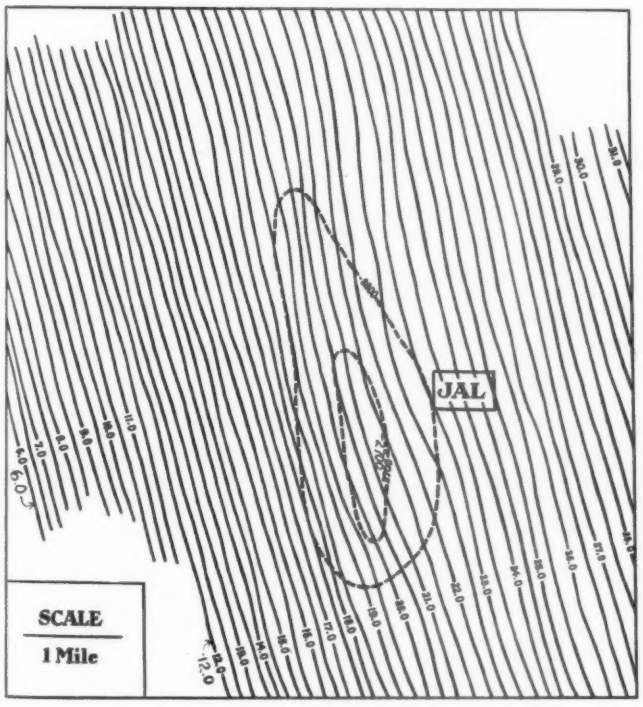


FIG. 4-C. Gravity anomaly of Fig. 4-A with regional gradient added.

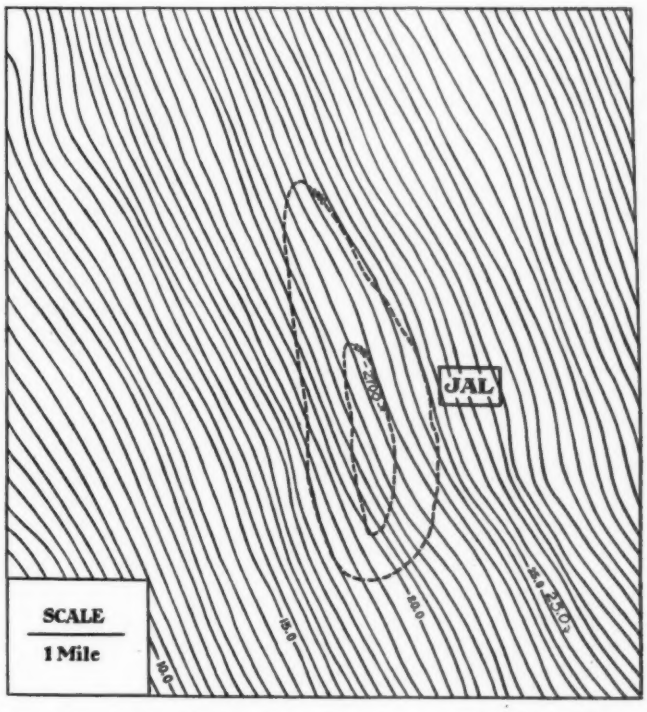


FIG. 4-D. Observed gravity of area covered by Fig. 4-A. Comparison with Fig. 4-C shows similarity of anomalies immediately west of village of Jal. Need of carefully planned survey in such areas is apparent.

four years calls for a critical study as to the methods of conducting these surveys and the interpretation of the data. This type of exploration will doubtless repeat the mistakes of seismic exploration where conclusions were made erroneously with inadequate control and too little, or no, attention was paid to anomalous data just because we thought them incorrect.

Emphasis is given to the discussion of the low-cost geophysical methods not because they are the most important—they are not—but because the data provided by these methods have been so mistreated and so misunderstood that an explanation of some of their possibilities and limitations is in order. Up to a certain point the problem of interpreting gravity and magnetic data is geophysical; beyond this point the problem becomes geological, demanding an intimate knowledge of the regional and local geology of the area involved.

Although it is true that several different distributions of materials of different density can be devised to satisfy any given gravity profile, the range of the geologically acceptable circumstances that will provide the given profile can be limited. It is possible to restrict this range of probable answers well within that commonly thought possible by a

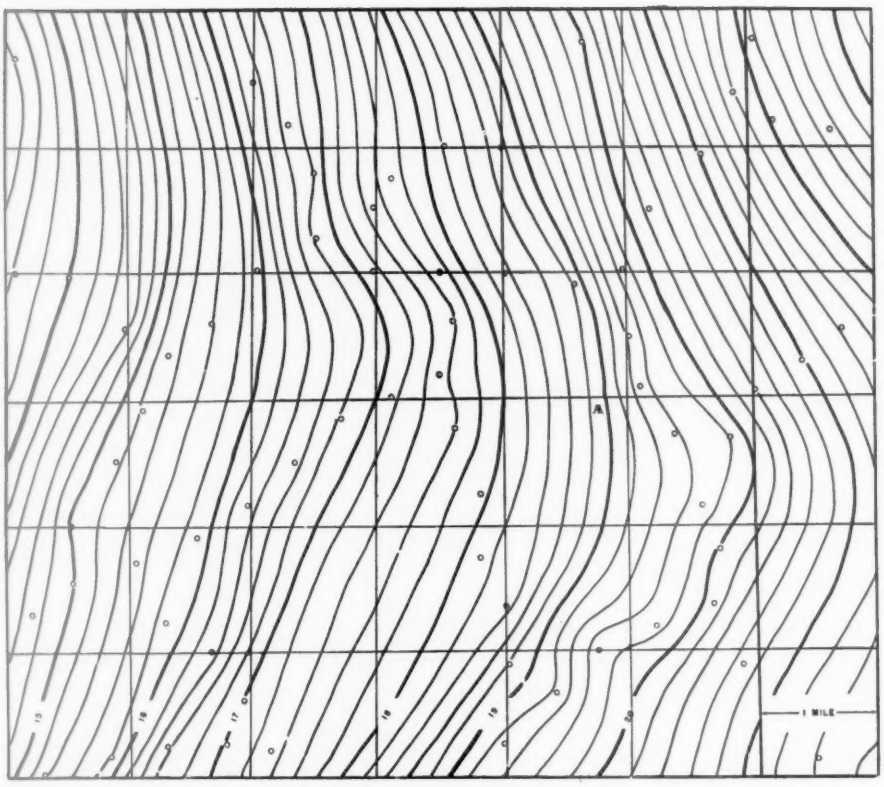


FIG. 5-A. Gravity contours from reconnaissance survey of area in Mississippi. Salt dome is suspected in vicinity of *A*. Location of observations indicated by circles; contour interval, 0.2 milligal.

proper application of techniques that can be developed by the geologist.

Although the gravity meter measures the total gravitational effects at a given point, those due to the differences in the densities of rocks involved in the section to be drilled are of the most concern. Inasmuch as irregularities in the distribution of these densities due to structural deformation mark the areas of interest, it becomes fundamental to determine these differences in density.

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Fortunately, the whole scheme is subject to a fairly rigid test. The gravity anomaly of a known structure well controlled by subsurface data can be computed from the density data at hand and checked against an actual field survey. If the comparison is proved satisfactory, confidence is established in the method and the possibilities of using the gravity meter effectively. Measured by such standards numerous gravity surveys fall far short of accomplishing the thing they were designed to do.

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The Shoshone anticline is outlined in Fig. 3-A, which with the densities of the formations involved permits the determination of the gravity effect at as many points as desired. Fig. 3-B, resulting from such a computation, outlines the gravity effects of the structure only. To these effects has been added a regional gradient determined by study of the regional gravity map. Fig. 3-C outlines this combination, which can be compared with the observed gravity Fig. 3-D. The two maps agree that the total anomaly is approximately 3 milligals. The greater length of the anomaly outlined by the observed gravity is due to the inaccuracies of the original structural map and an inadequate number of stations computed.

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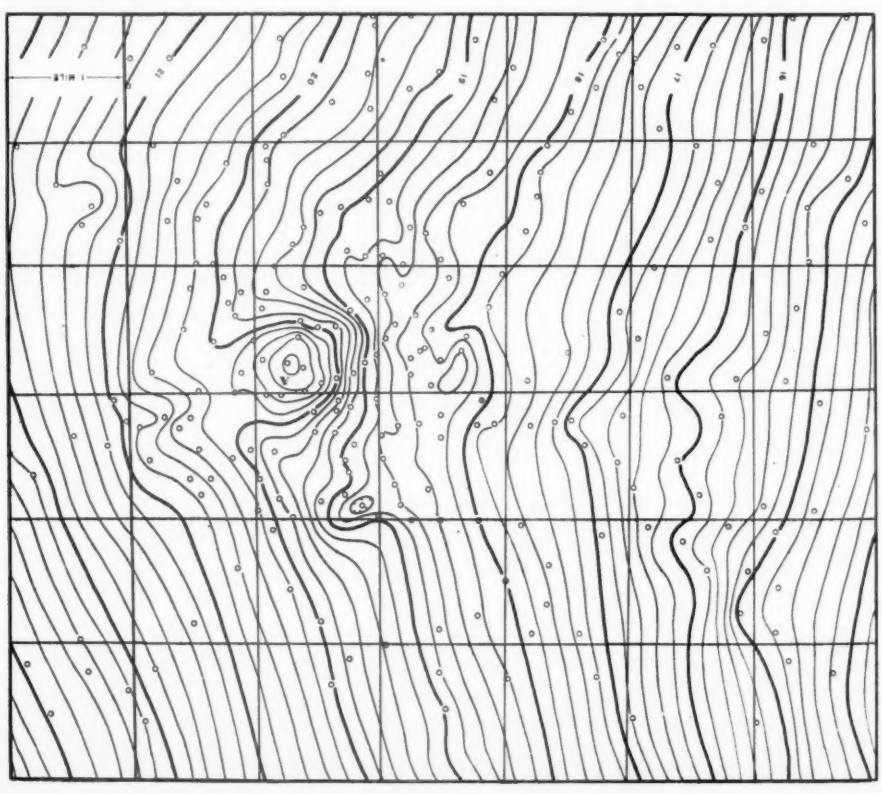

FIG. 5-B. Gravity contours from detailed survey of area shown in Fig. 5-A. Evidence of "caprock" indicates piercement salt dome confirmed by subsequent drilling. Note observations indicating presence of "cap" limited to one square mile.

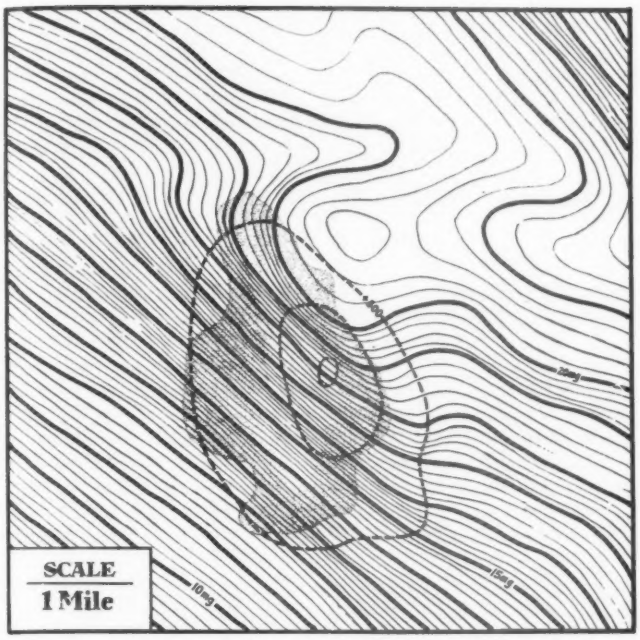

FIG. 6-A. Gravity contours over Altus field, in Jackson County, Oklahoma. Dashed contours, outline, by 100-ft intervals, structure on top of Canyon formation. Stippling encloses productive area.

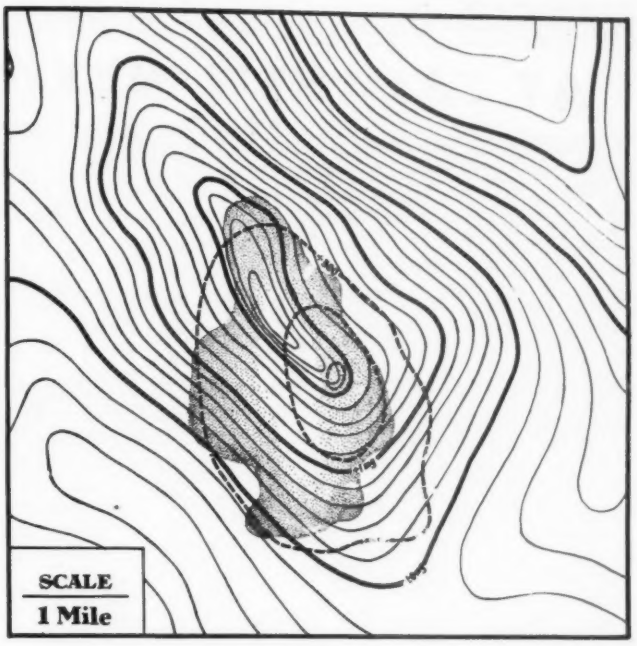

FIG. 6-B. Residual gravity map of Altus pool shown in Fig. 6-A.

Jal. The computed anomaly is mapped on Fig. 4-B. In order to make a comparison with the observed gravity Fig. 4-D, it becomes necessary to add to the local anomaly a regional gradient; this combination is shown in Fig. 4-C. A comparison of Fig. 4-C and Fig. 4-D shows the similarity of the anomaly immediately west of Jal. A survey capable of detecting this structure need be planned with care. The anomaly noted southeast of Jal on the observed gravity map is the expression of a second structural feature in this vicinity that was not considered in the calculated gravity effects of the Jal structure.

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Few gravity surveys can be properly completed without an intimate knowledge of the geology of the surface formation. Different formations at outcrop generally require a change in density factors used and the limitations of probable error in terrane correction and other near-surface effects are better understood by field observations. Such information is obtained best in the field by a geologist who understands the geophysical problem.

A further analysis of gravity interpretation includes a brief discussion of important phases of the problem.

● **Direct interpretation of local anomalies in terms of local structure.** The ability of the gravity method to outline local structures requiring no further exploration ahead of the drilling operation is possible only in limited areas. The exploration of salt domes is, of course, an example of gravity work at its best. Other areas, however, have been explored by this method to the point requiring little, if any, additional expenditures ahead of the drilling operation.

Any structure having considerable vertical relief that brings formations with pronounced density contrasts near the surface can be outlined by the gravity method. The adequacy of such exploration is determined by the depth to the interface bounding the formations of different density, the density contrast, the vertical height of the structure and its width.

The Altus structure in Jackson County of southern Oklahoma is outlined well by this method (Figs. 6-A and B). Similar structures that can be explored with equal satisfaction, are commonly found adjacent to uplifts bringing pre-Cambrian formations or massive limestones to shallow depths. The Hobbs field, in Lea County, New Mexico, which is a large structure buried at considerable depth, was discovered by gravity and magnetic exploration. No other exploration preceded the drilling of the discovery well.

It is of interest in retrospect to note how adequately gravity exploration did outline prospective fields, although other types of exploration were subsequently employed. The Stratford dome drilled by the Indian Territory Illuminating Oil Company in the Texas Panhandle, in Sherman County, Texas, provides an example. The writer is advised that this company took the original block on the basis of magnetic exploration and completed some additional work prior to drilling the first well.

An analysis of the gravity Fig. 7-A and B, and magnetic data Fig. 7-C, in the vicinity of this structure is of special interest. Both types of exploration have done marvelously well in outlining the interesting area and afford opportunity to emphasize the need of understanding the geological factors involved. The density and magnetic characteristics of the sediments and pre-Cambrian rocks encountered in a deep well drilled on this structure have been determined by laboratory study and have made possible the construction of the profiles shown.

The gravity anomaly is due largely to the structural relief of the brown dolomite at a depth of 2000 ft and its density contrast with the overlying redbeds. The magnetic anomaly is due to the structural relief of the pre-Cambrian rocks at the depth of 5000 ft.

A comparison of the gravity profile (Fig. 7-D, Gravity "A") computed from the known density contrasts and the structures outlined by drilled wells, with the observed profile provides a satisfactory fit. Any attempt to assign the density contrasts to any surface below the brown dolomite, such as the pre-Cambrian surface, gives a profile (Fig. 7-D, Gravity "B") so far removed from the observed as to leave no doubt as to which interpretation is preferable.

Three curves have been constructed of magnetic profiles (Fig. 7-D, Magnetic): One from the observed anomaly, a second (Magnetic "A") on the assumption that the magnetic effects are confined to the pre-Cambrian rocks, and a third (Magnetic "B") computed on the assumption that the magnetic effects emanate from some formation above the pre-Cambrian in the position of the

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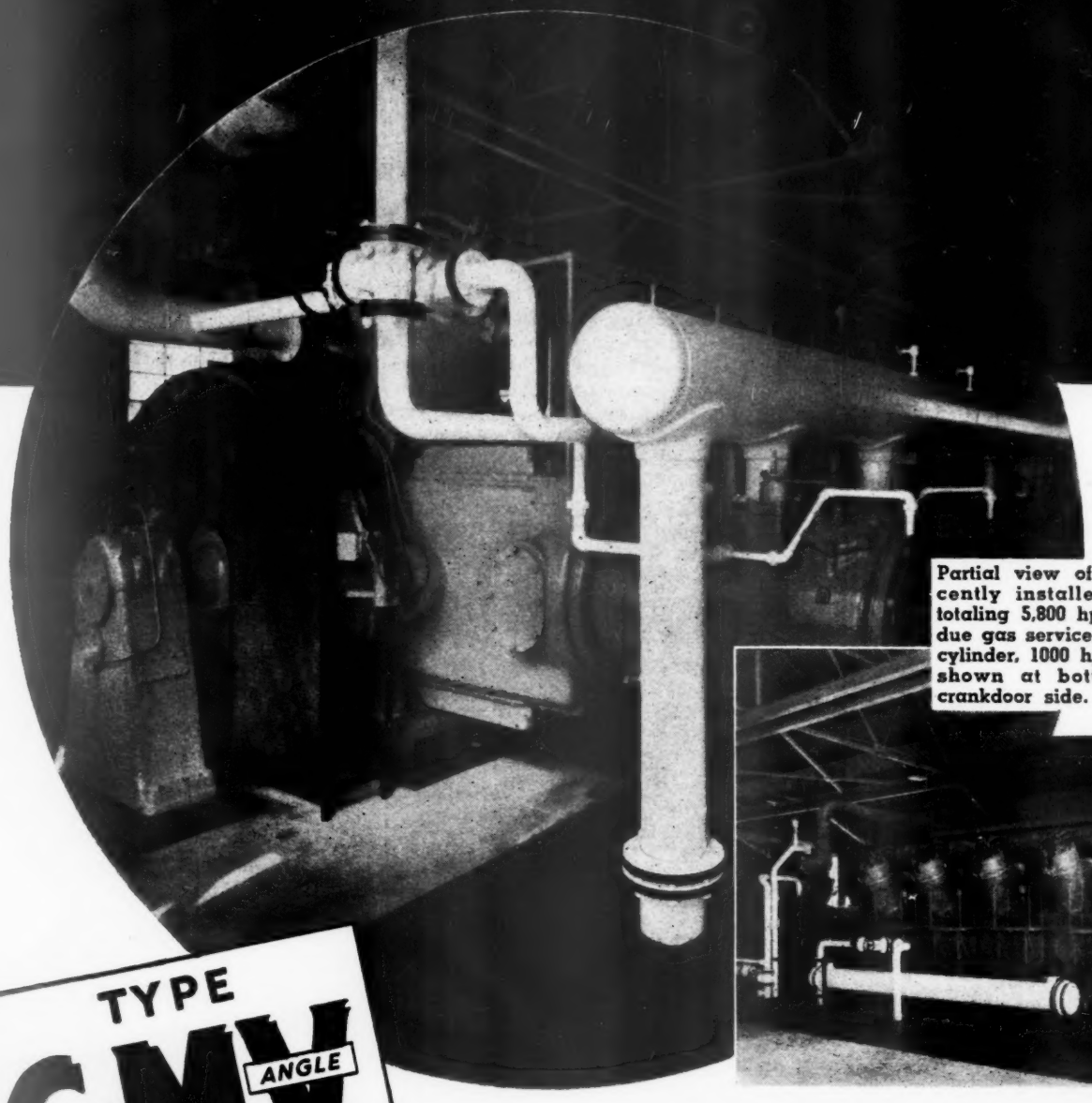
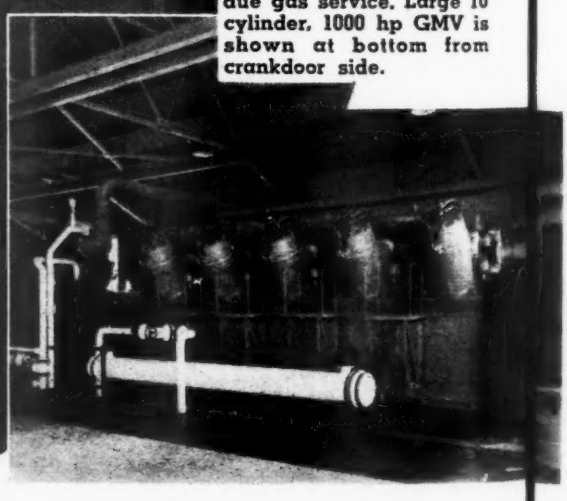


Partial view of most recently installed GMV's totaling 5,800 hp for residue gas service. Large 10 cylinder, 1000 hp GMV is shown at bottom from crankdoor side.



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THE photos on these pages give only an inkling of the 15,830 Cooper-Bessemer horsepower serving the El Paso Natural Gas Company at Jal, New Mexico. Most of the units are modern, long-lived GMV-angle compressors, with six, eight, and ten cylinder V-type engines, for pipe line transmission of field gas, for refrigeration service in gasoline extraction, and for transmission of residue gas into the main line system. Still other Cooper-Bessemers provide for repressuring, vapor re-compressing, and electrical power generation.

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brown dolomite. A comparison of these profiles proves that the observed magnetic anomaly is due to magnetically active beds at least at the depth of the pre-Cambrian. The lack of closer coincidence of the profile of the observed anomaly with the profile representing the effect of the pre-Cambrian rocks may be due to our inability to reconstruct accurately the pre-Cambrian surface.

The evidence clearly establishes the fact that two different geological factors are responsible for the observed geophysical anomalies. The formations involved are in this particular case 3000-ft apart. Correlative to the discussion at this point it seems possible in such a structure to predict roughly the thickness of sediments ahead of the drilling operation.

● **Use of gravity surveys to direct additional exploration.** Exploration by a gravity meter has low resolving power but is the means by which areas can be explored rapidly. Localizing areas of possible interest for intensive exploration by seismic or other means rightly commands a major part of the coordinated effort of this method in oil exploration. But the possible guidance of a properly processed and adequately controlled gravity survey should include much more than the simple expedient of indicating selected areas for further study. The greater value lies in the possibility of outlining the structural pattern of an unexplored area to point the way to the major features, and thus outline a long range program with emphasis on the major trends.

The analyses of a series of gravity anomalies can place them in an order of preference with intervening areas of doubtful value. A properly planned seismic exploration program that discovers the focal points of interest or the trends

FIG. 7-A. Gravity contours over Stafford field, in Sherman County, Texas. Dashed contour lines from structural map on top of Brown dolomite.

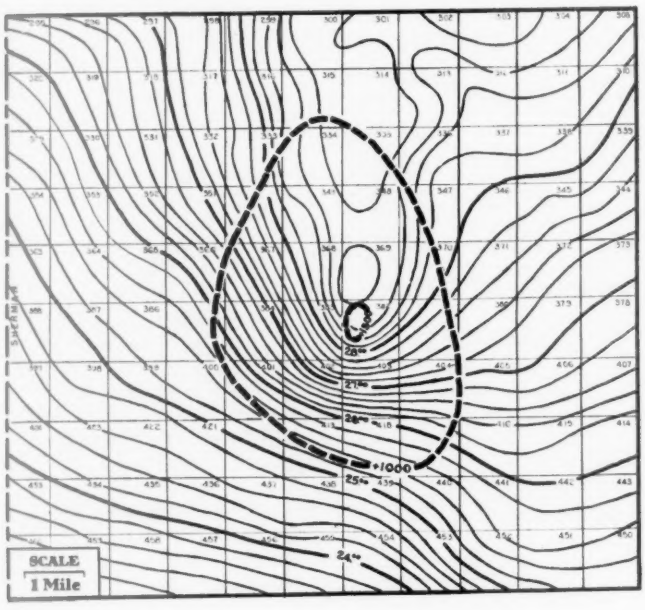


FIG. 7-B. Residual gravity map of Stafford field shown in Fig. 7-A.

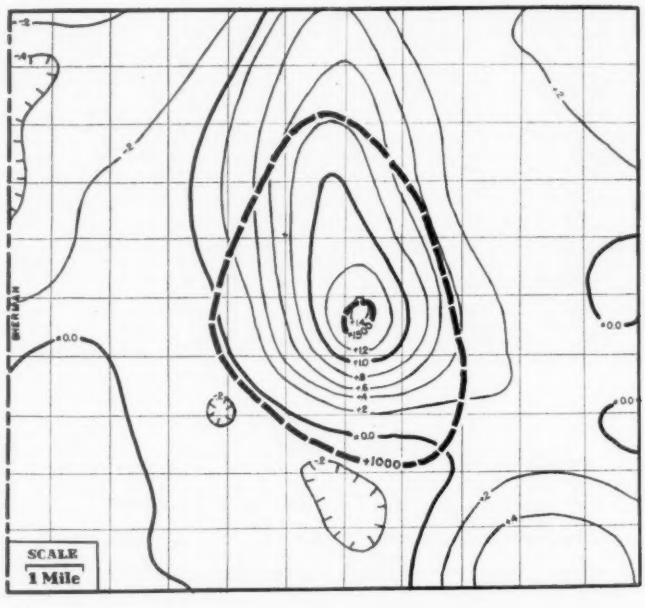


FIG. 7-C. Magnetic contours over Stafford field shown in Fig. 7-A. Contour interval, 25 gammas.

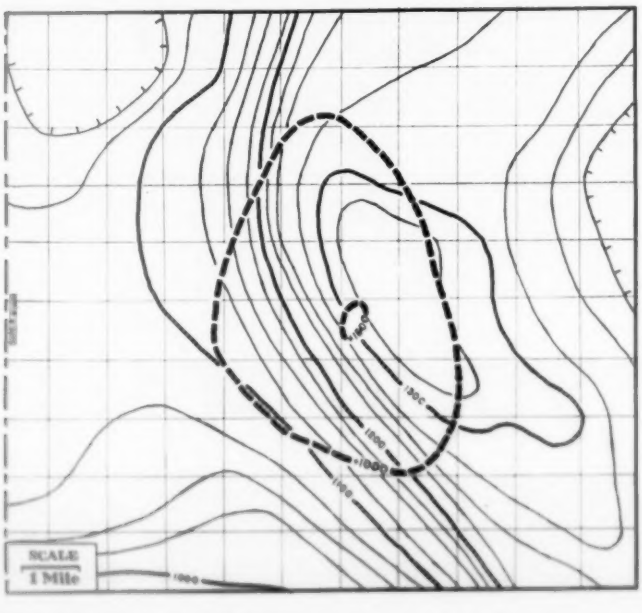
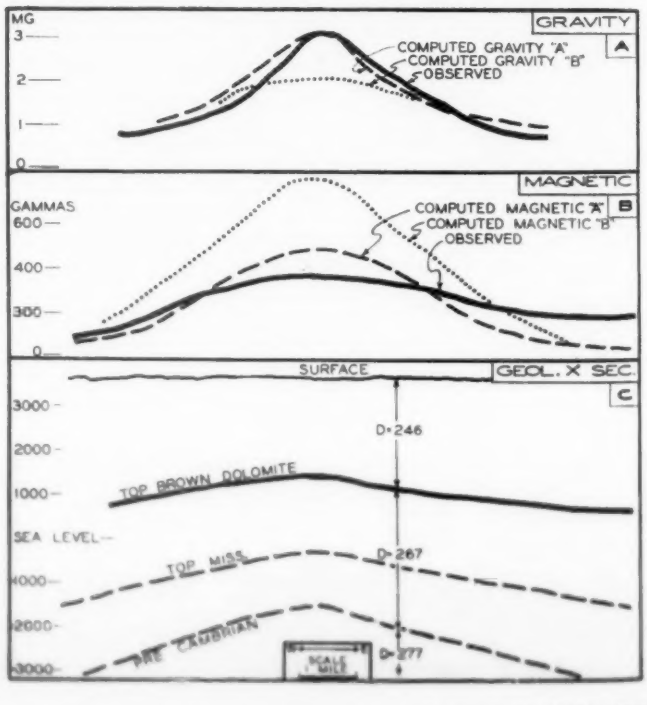
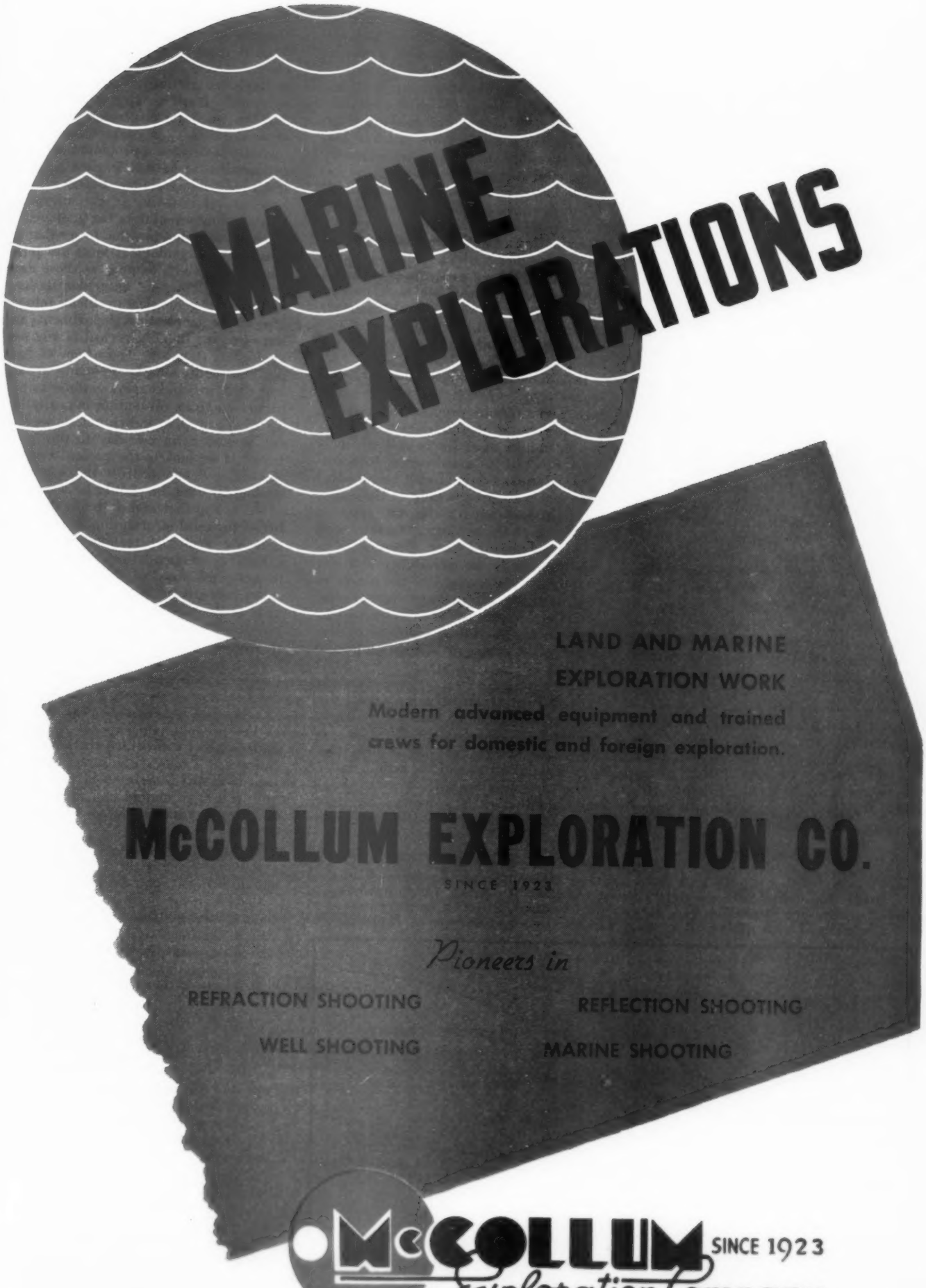


FIG. 7-D. Geological cross section of Stafford field shown in Fig. 7-A with gravity and magnetic profiles. Observed profiles (heavy lines) compare favorably with values (dashed lines) of computed gravity "A" and computed magnetic "A".

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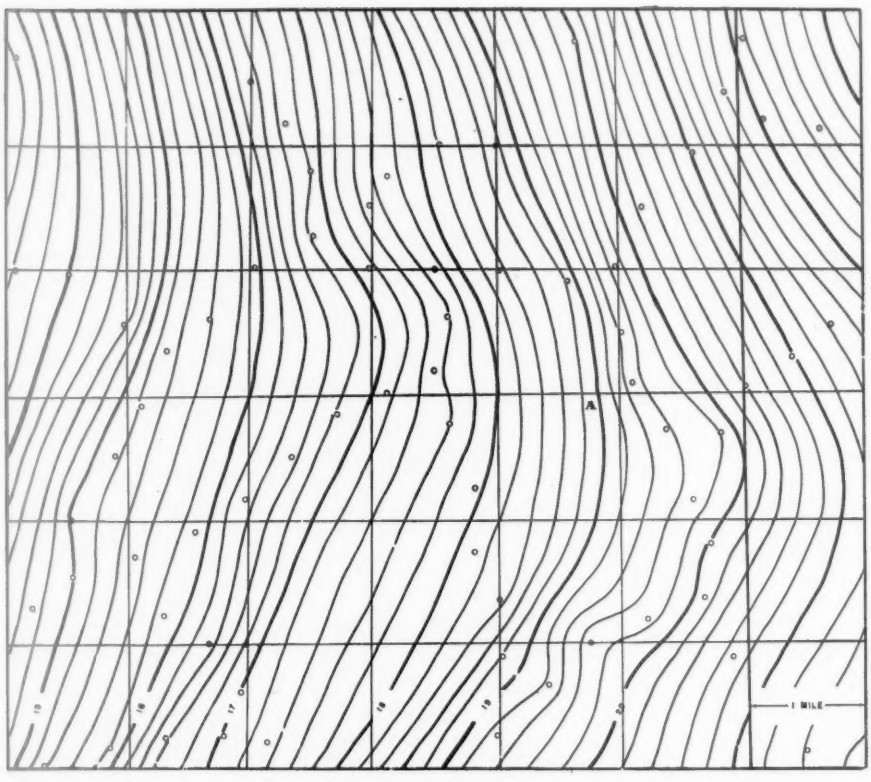

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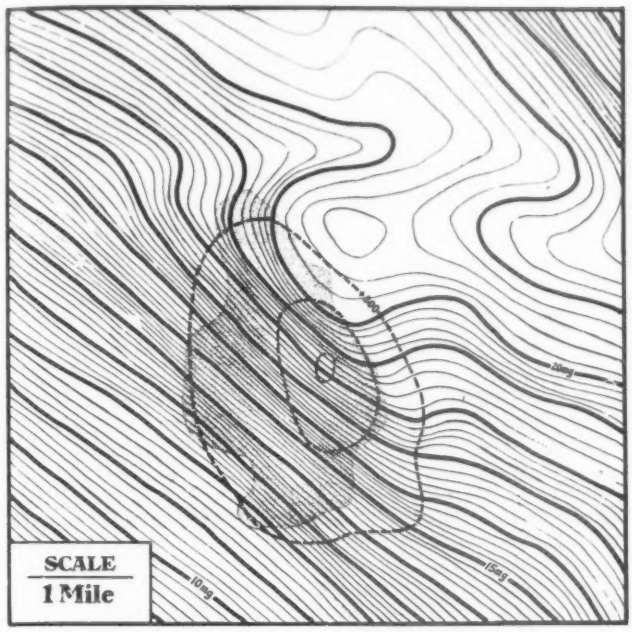

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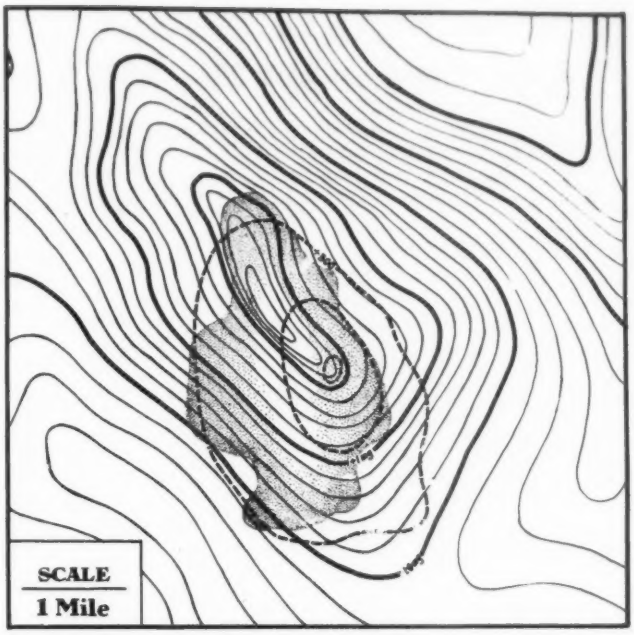

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Any structure having considerable vertical relief that brings formations with pronounced density contrasts near the surface can be outlined by the gravity method. The adequacy of such exploration is determined by the depth to the interface bounding the formations of different density, the density contrast, the vertical height of the structure and its width.

The Altus structure in Jackson County of southern Oklahoma is outlined well by this method (Figs. 6-A and B). Similar structures that can be explored with equal satisfaction, are commonly found adjacent to uplifts bringing pre-Cambrian formations or massive limestones to shallow depths. The Hobbs field, in Lea County, New Mexico, which is a large structure buried at considerable depth, was discovered by gravity and magnetic exploration. No other exploration preceded the drilling of the discovery well.

It is of interest in retrospect to note how adequately gravity exploration did outline prospective fields, although other types of exploration were subsequently employed. The Stratford dome drilled by the Indian Territory Illuminating Oil Company in the Texas Panhandle, in Sherman County, Texas, provides an example. The writer is advised that this company took the original block on the basis of magnetic exploration and completed some additional work prior to drilling the first well.

An analysis of the gravity Fig. 7-A and B, and magnetic data Fig. 7-C, in the vicinity of this structure is of special interest. Both types of exploration have done marvelously well in outlining the interesting area and afford opportunity to emphasize the need of understanding the geological factors involved. The density and magnetic characteristics of the sediments and pre-Cambrian rocks encountered in a deep well drilled on this structure have been determined by laboratory study and have made possible the construction of the profiles shown.

The gravity anomaly is due largely to the structural relief of the brown dolomite at a depth of 2000 ft and its density contrast with the overlying redbeds. The magnetic anomaly is due to the structural relief of the pre-Cambrian rocks at the depth of 5000 ft.

A comparison of the gravity profile (Fig. 7-D, Gravity "A") computed from the known density contrasts and the structures outlined by drilled wells, with the observed profile provides a satisfactory fit. Any attempt to assign the density contrasts to any surface below the brown dolomite, such as the pre-Cambrian surface, gives a profile (Fig. 7-D, Gravity "B") so far removed from the observed as to leave no doubt as to which interpretation is preferable.

Three curves have been constructed of magnetic profiles (Fig. 7-D, Magnetic): One from the observed anomaly, a second (Magnetic "A") on the assumption that the magnetic effects are confined to the pre-Cambrian rocks, and a third (Magnetic "B") computed on the assumption that the magnetic effects emanate from some formation above the pre-Cambrian in the position of the

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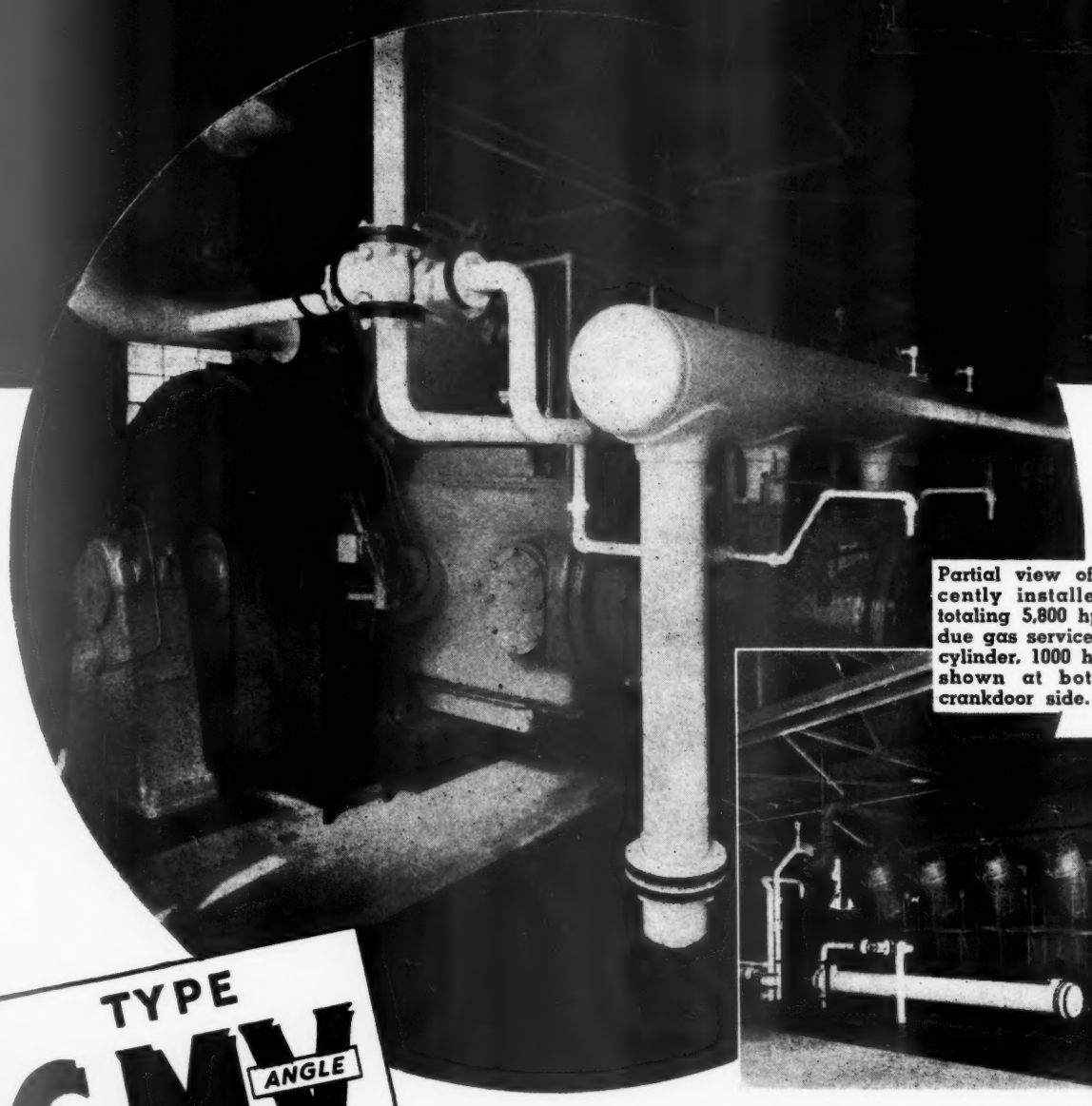
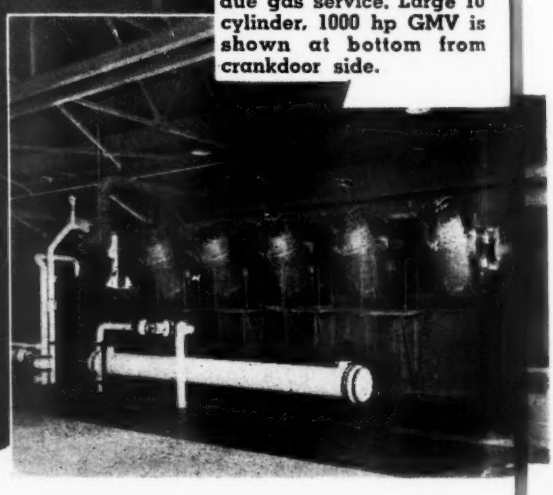


Partial view of most recently installed GMV's totaling 5,800 hp for residue gas service. Large 10 cylinder, 1000 hp GMV is shown at bottom from crankdoor side.



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brown dolomite. A comparison of these profiles proves that the observed magnetic anomaly is due to magnetically active beds at least at the depth of the pre-Cambrian. The lack of closer coincidence of the profile of the observed anomaly with the profile representing the effect of the pre-Cambrian rocks may be due to our inability to reconstruct accurately the pre-Cambrian surface.

The evidence clearly establishes the fact that two different geological factors are responsible for the observed geophysical anomalies. The formations involved are in this particular case 3000 ft apart. Correlative to the discussion at this point it seems possible in such a structure to predict roughly the thickness of sediments ahead of the drilling operation.

● **Use of gravity surveys to direct additional exploration.** Exploration by a gravity meter has low resolving power but is the means by which areas can be explored rapidly. Localizing areas of possible interest for intensive exploration by seismic or other means rightly commands a major part of the coordinated effort of this method in oil exploration. But the possible guidance of a properly processed and adequately controlled gravity survey should include much more than the simple expedient of indicating selected areas for further study. The greater value lies in the possibility of outlining the structural pattern of an unexplored area to point the way to the major features, and thus outline a long range program with emphasis on the major trends.

The analyses of a series of gravity anomalies can place them in an order of preference with intervening areas of doubtful value. A properly planned seismic exploration program that discovers the focal points of interest or the trends

FIG. 7-A. Gravity contours over Stafford field, in Sherman County, Texas. Dashed contour lines from structural map on top of Brown dolomite.

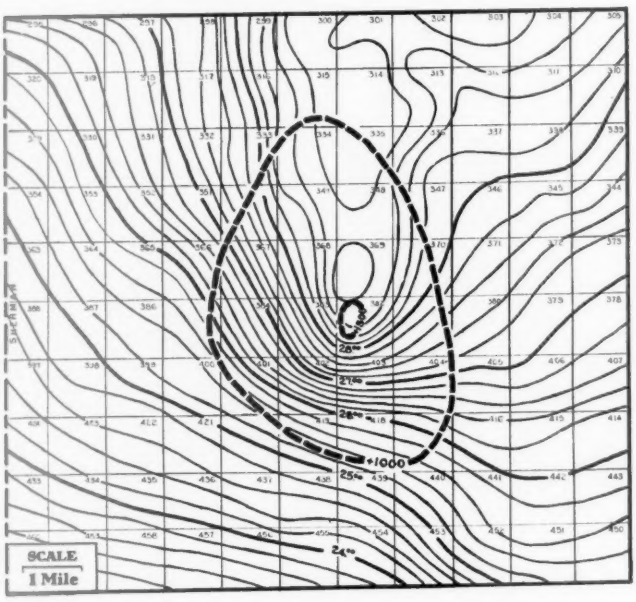


FIG. 7-B. Residual gravity map of Stafford field shown in Fig. 7-A.

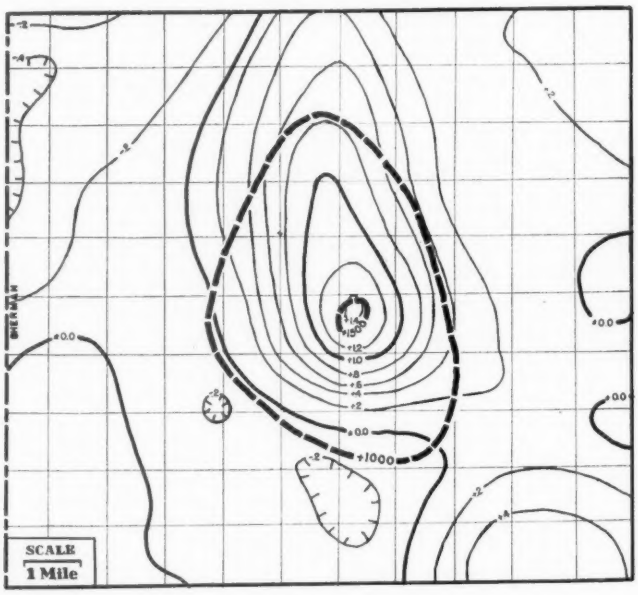


FIG. 7-C. Magnetic contours over Stafford field shown in Fig. 7-A. Contour interval, 25 gammas.

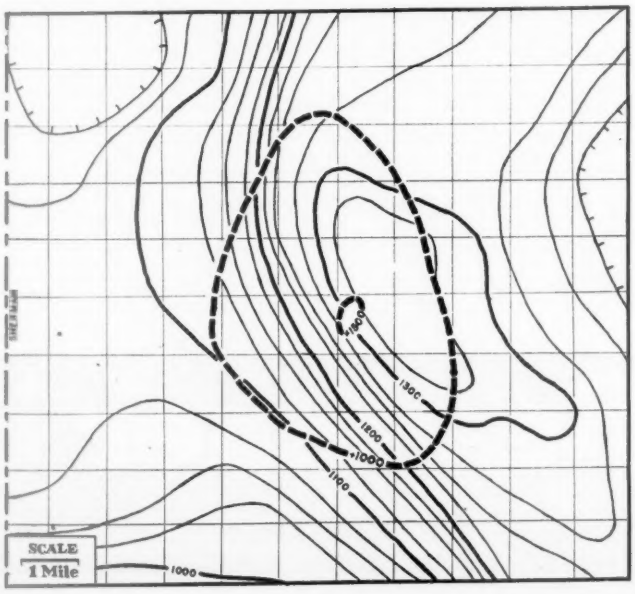
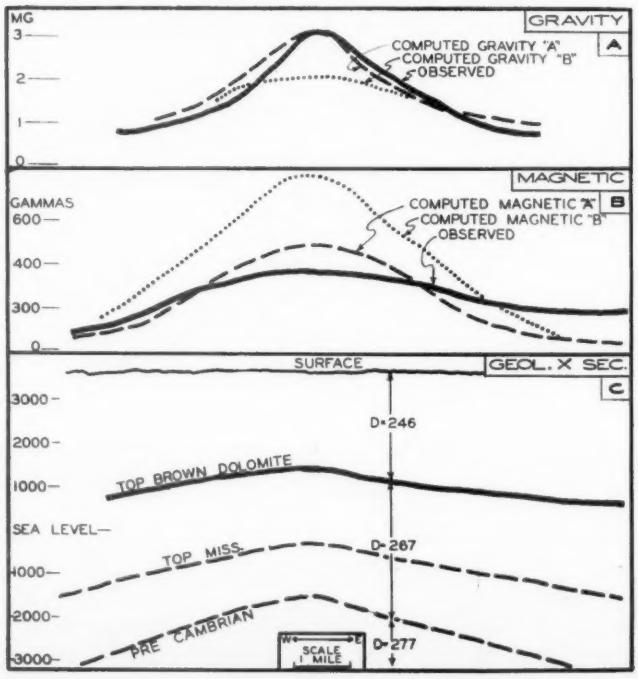


FIG. 7-D. Geological cross section of Stafford field shown in Fig. 7-A with gravity and magnetic profiles. Observed profiles (heavy lines) compare favorably with values (dashed lines) of computed gravity "A" and computed magnetic "A".



Oil is Found!

Exploration for oil has now covered much of the world, yet new pools are consistently being discovered in areas previously over-looked. Credit must go to the scientists and engineers, the men who use the most modern methods of determining where oil may be found. Today, oil is discovered on the drawing board, in the laboratory, in the field equipment and interpretation offices of the technicians utilizing precision seismic surveys to indicate sub-surface formations.

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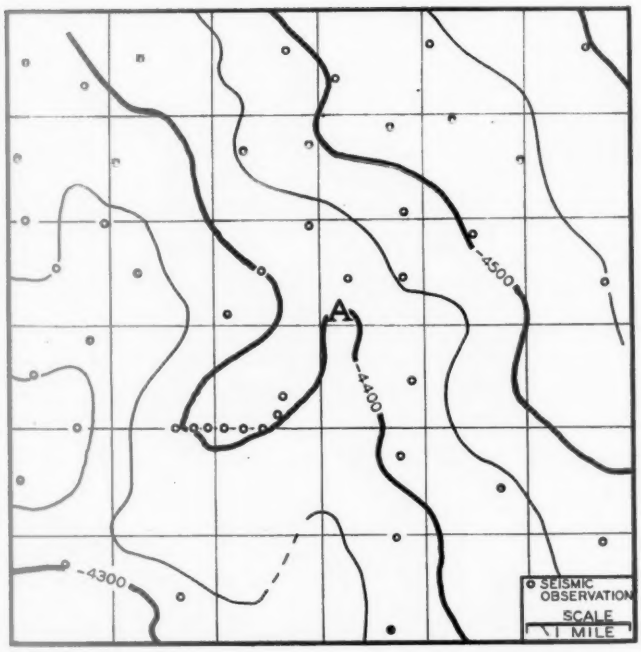


FIG. 8-A. Contour map from seismic survey of area in Mississippi. Circles indicate points of observation. Note syncline outlined southwest of "A".

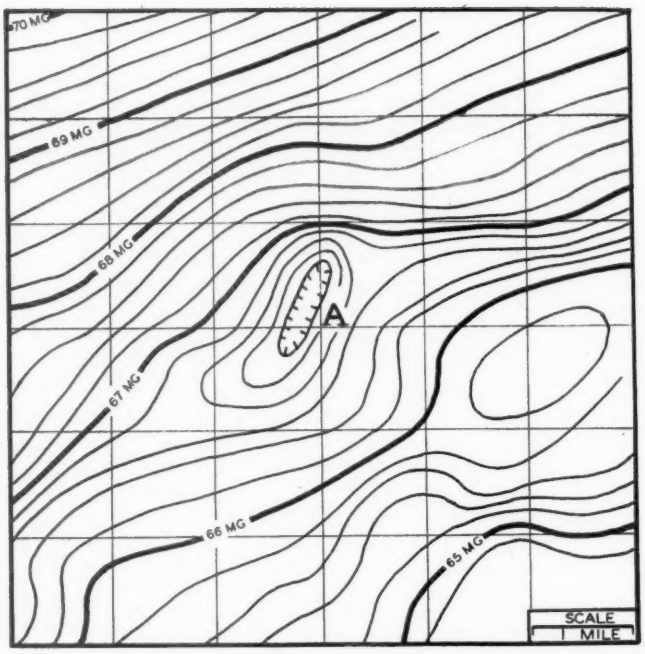


FIG. 8-B. Gravity map of area outlined in Fig. 8-A. Anomaly near point *A* is obvious and throws doubt upon adequacy of seismic map.

in a given area early in the investigation has many advantages and can complete the work with a minimum of time and expense.

Frequently an exploration method suitable for the average problem in a given province needs modification in selected areas to give proper emphasis to areas of deep-seated structural anomalies. Gravity surveys have pointed the way to many such areas where special effort has revealed features of interest not suspected by the original work. Fig. 8-A is the result of a reconnaissance seismic survey that presumably adequately explored the area. A study of the gravity map (Fig. 8-B) prompted additional detailed work which provided a map (Fig. 8-C) unlike the original one.

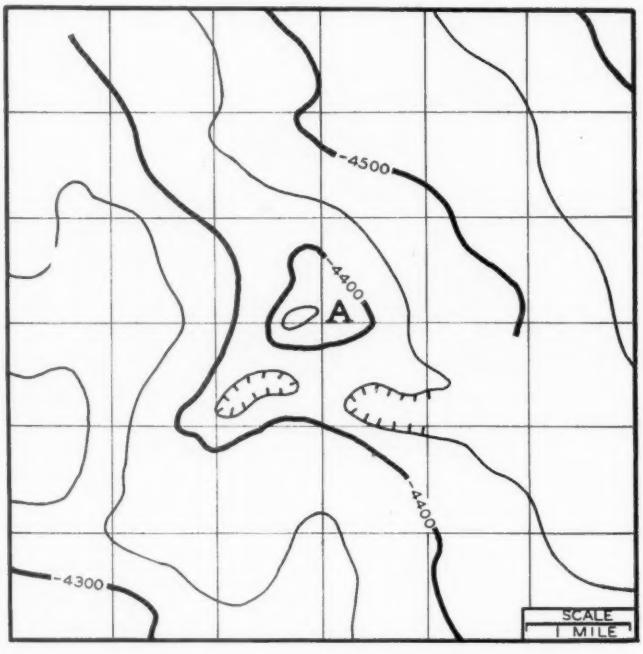


FIG. 8-C. Final seismic map of area shown in Fig. 8-A after resurvey with detailed work. Although structural anomaly at *A* is small, it may be of interest in deeper strata.

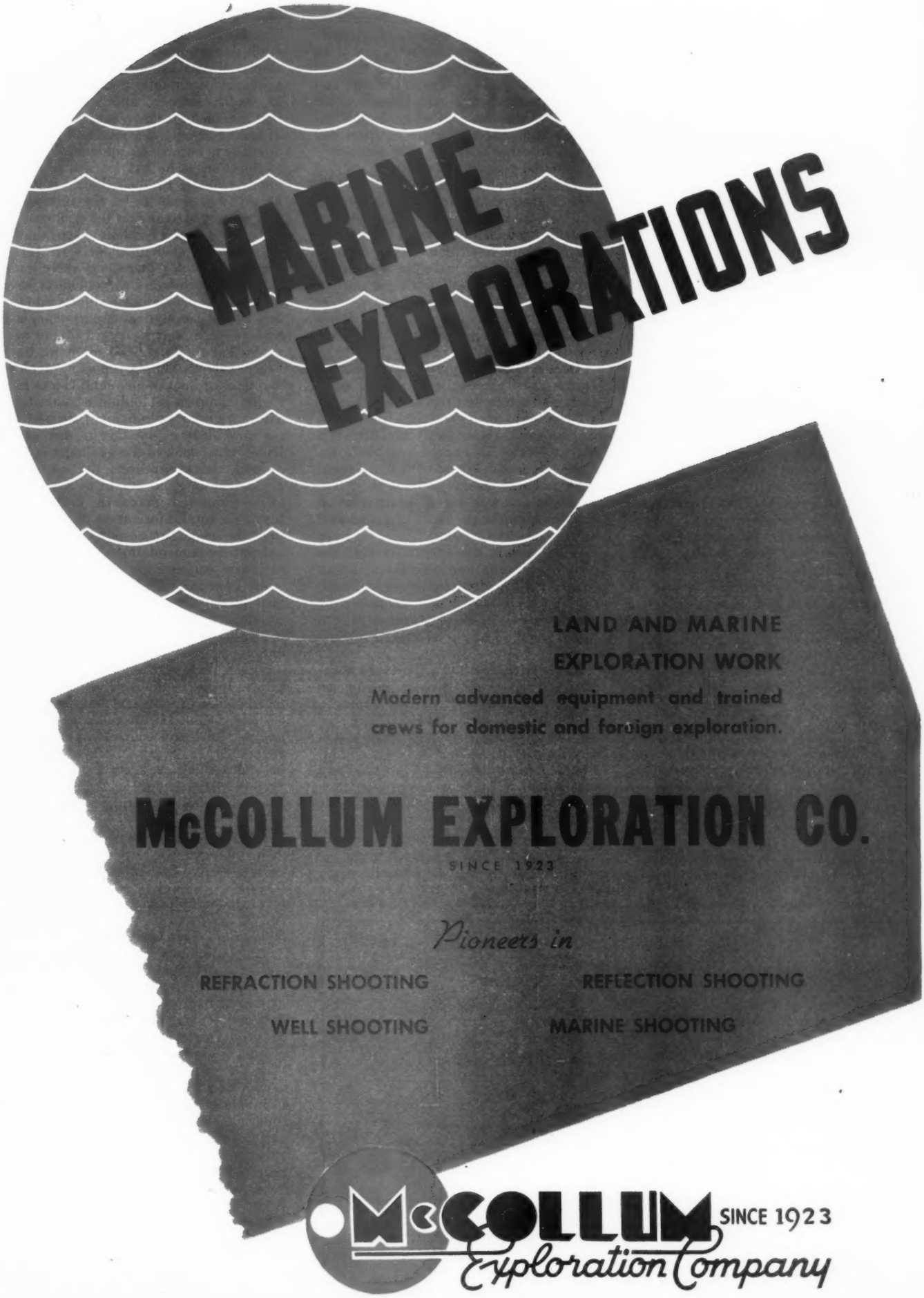
● **Analysis of gravity data as aid to questionable geological interpretation.** The analysis of gravity data can be used frequently to select the more probable of two alternate interpretations of geological information. Occasionally it can be used to prove that an existing interpretation of subsurface information can not prevail, even though it cannot provide a solution that is unique.

With an accurate knowledge of the density characteristics of a sedimentary section, the anomaly that would be produced by any supposed structure can be computed. Frequently a comparison of such a computed anomaly with the observed gravity will make it necessary to discard the supposed structure as geologically impossible. Even if the method may not provide a unique interpretation, to prove the geological interpretation wrong or unlikely is to make a substantial contribution to the exploration effort.

The geologist is aided frequently by the application of the simplest concepts of the use of gravity maps. The geologist working in a basin known to have salt intrusions, such as the East Texas basin, is naturally inclined to assume that all wells not known to be structurally low are on some part of a salt uplift. With a "salt dome consciousness" the geologist outlines all his structures as salt domes and his map, wherever possible, is a series of circular uplifts tangent to each other. The use of a gravity map will immediately classify the "salt uplifts" into those which are probable and those which do not likely exist.

Faulting commonly provides the most prominent density contrasts to be found in gravity exploration. Obviously, the distribution of density contrasts due to thrust faulting is unlike that produced by normal faulting of equal vertical displacement. Occasionally these differences are such that a gravity survey will suggest the type of disturbance. The construction of gravity profile assuming a normal fault may differ so much from one constructed on the basis of a thrust that a comparison of both profiles with the observed profile will suggest the nature of the faulting. An illustration of such a problem is presented later.

● **Use of gravity data in study of regional geology.** Where the regional gravity features are not obscured by isostatic adjustments, or other extraneous effects, the gravity information can be used frequently to give important clues as to the regional geology. These regional features may be of the utmost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importance in suggesting the major structural trends of the area or in bounding interesting provinces having a common geological history.

The possible extension and limits of the Appalachian environment are suggested by the "grain" of the regional gravity and magnetic features in Georgia and Florida. The possible limits of basins within which salt movement of considerable proportions has taken place are suggested by certain regional gravity maps.

The faulted zone in southeastern Oklahoma, which is bounded on the west by the Choctaw fault, has a width of 50 miles. The regional gravity features point to the probability that this zone must be narrowed to 40 miles or less in the latitude of Dallas, and still less south of this point. Certain possible interpretations of the mechanics of this zone are suggested by the major gravity features but can not be discussed in this paper.

Regional gravity surveys on the southwest side of the Wind River Mountains, in Wyoming, provide evidence of the thrust character of these mountains. Fig. 9 outlines an observed gravity profile across this mountain front. Three computed profiles are shown using density contrasts which can be assigned to the beds involved with some confidence. One is computed on the assumption of a normal fault of 30° hade, a second on the assumption of a vertical fault, and a third on a basis of 45° angle thrust. A comparison of these profiles favors the thrust character of the faulting.

Problems on a smaller scale lend themselves to a similar analysis wherever beds of considerable thickness but of distinctly different density contrasts are brought in contact by faulting.

● **Advantages of acquainting geologists with geophysical concepts.** We have discussed for years the problem of how best to coordinate the work of the geologists and geophysicists. The following suggestions may not be new to many exploration units, but for some it may be a bit "left of center" or "right of center," depending upon the viewpoint. With emphasis on the better use of the low cost methods, the problem of geological interpretation becomes more involved and solutions other than the ones commonly considered suggest themselves.

The constant accumulation of quantities of geophysical data of many different sorts makes stupendous the problem of evaluating all of these data in terms of current problems which change rapidly. The many different procedures by which this can be done will not be a part of this analysis; however, one important phase of the problem follows that has tremendous possibilities of making better use of geophysical data.

Does it occur to you that the district or "grass roots" geologist may have many facts and alternate proposals explaining a given set of geological data besides the one he thinks most likely and which is the subject of his usual report with recommendations? Armed with geophysical data and with proper help in their use, he might find that his alternate solution satisfies both the geological facts as well as the geophysical data. Correlative to this thought is the possibility that the geophysical data would be the means of suggesting the alternate geological solution. Certainly, much is to be gained by a proper analysis of the geophysical data at the point of origin of new geological ideas.

The writer does not propose to make geophysicists of our "district" geologists, but he does contend that the geologist can be made to understand the basic geophysical concepts of the several geophysical methods and so better understand the limitation of each method and the data that each provides. Certainly, the possibilities of unpredicted velocity changes in the weathered layer and changes in its thickness are no more difficult to comprehend than the use of the electrical and gamma-ray logs that the geologist continually interprets. He can as readily learn to appreciate the fact that an unconformity may bring beds of unlike density in contact in sufficient quantity to become a problem for gravity exploration as he has learned to correlated insoluble residues. Faced with the necessity of assisting in the interpretation of geophysical data the geologist on the ground is in a position to see that the best possible geological facts are forthcoming by which to process these data.

Too frequently we as geologists have dumped our geological problems into the laps of the geophysical departments and have become inert in regard to any new geological thinking. Too often we have become scouts simply reporting geological data or bookkeepers and clerks in a highly complex oil-finding organization. To what group, or individual, do we look for new ideas in our day to day problems? If we look to the geologist on the ground, the one nearest the source of geological data, he should be a member of the group that makes the final assembly of the total information. It is obvious that the geologist responsible for the current recommendations should be able to grasp geophysical concepts.

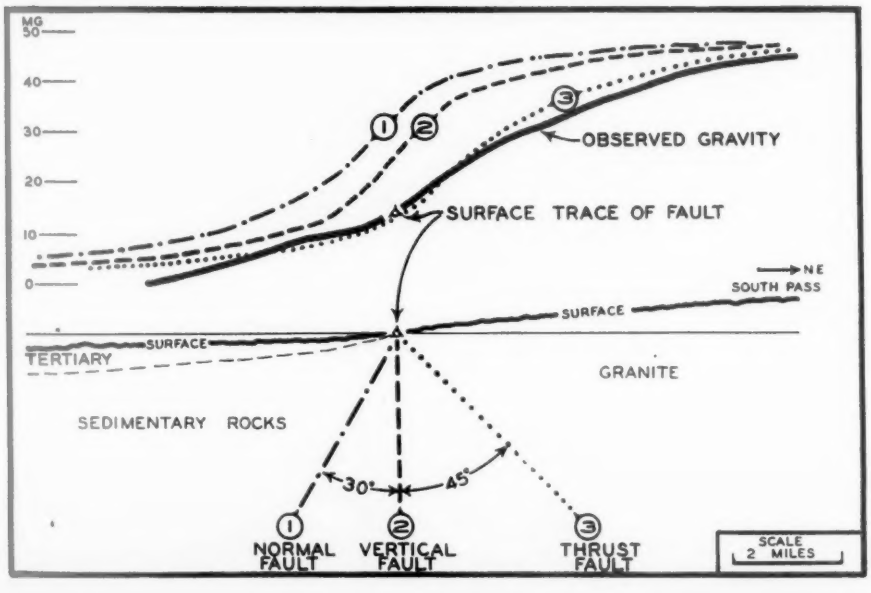
An increase in the number of geologists in the Society of Exploration Geophysicists marks a trend, however small, in the right direction. In 1940 approximately 7 per cent of our members had qualified and were on the roles of the S.E.G. In 1945 almost 9 per cent held membership in both societies. Inasmuch as the predominate expense of the oil-finding effort with which the geologist is concerned is so overwhelmingly geophysical, and will remain so in the foreseeable future, it should concern all of us to see that these percentages reach higher levels.

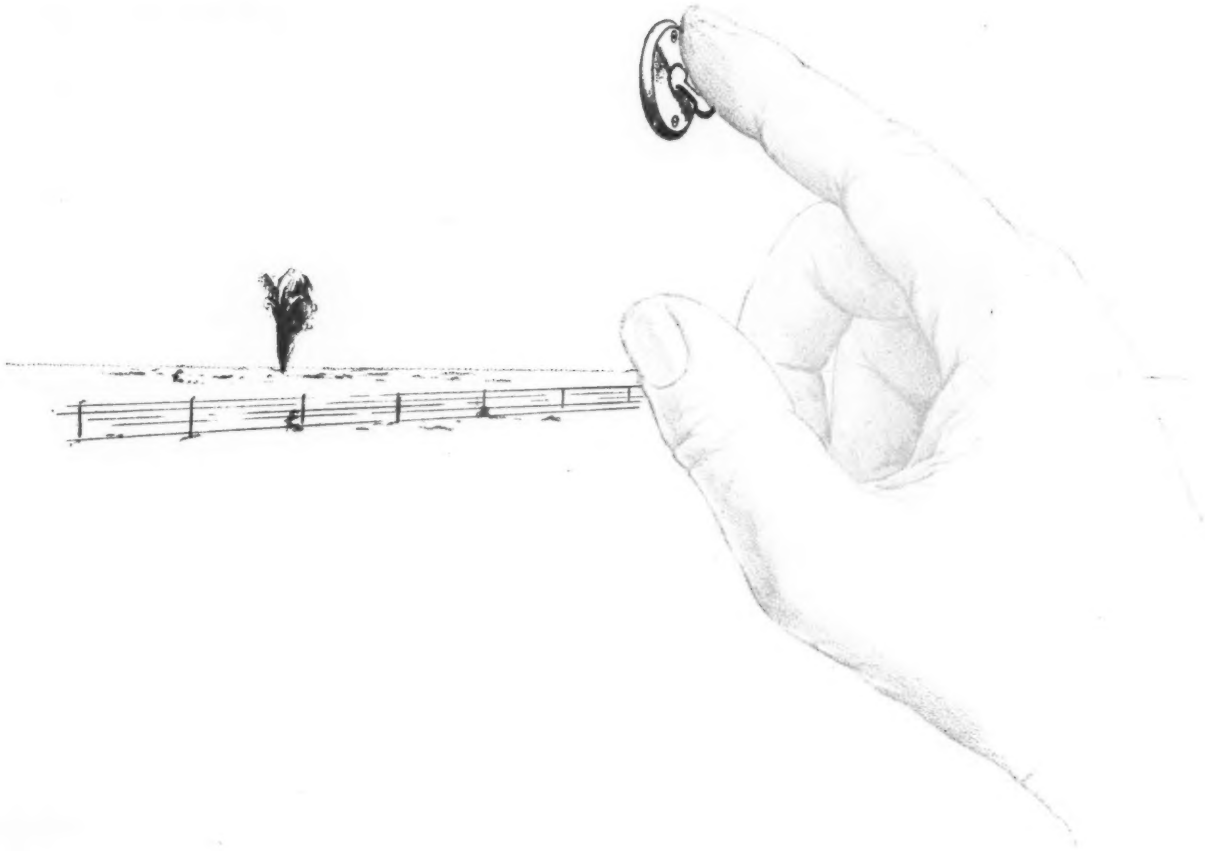
The most important reason the geologist, and especially the district geologist, should become acquainted with geophysical data to the point where he can use them under guidance is that such data can be the means of stimulating his imagination toward the birth of new ideas.

The optimum in geological-geophysical interpretation will be reached when one individual, or group of individuals, acts as a focus for all the geophysical data and geological information for final analysis. Obviously, the geologist on the ground who presumably is most familiar with the problems must be one of this group, and insofar as it is possible for members of this group to grasp the significance of any or all of the geophysical and geological data, in just this measure will the fullest possible use be made of the information.

Give the geologist to whom you look for new ideas freer access to geophysical information and instruct him in its interpretation. Such a scheme will stimulate his imagination and at the same time have it under control, thus providing the controlled imagination needed in our geological thinking. ★ ★ ★

FIG. 9. Gravity profile and cross section on southwest flank of Wind River Mountains, Sublette and Fremont counties, Wyoming. Computations of gravity are shown for (1) normal, (2) vertical, and (3) thrust faults. Comparison with observed gravity favors thrust character of faulting.





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Geothermal gradients in Mid-Continent and Gulf Coast oil fields*

By EARL A. NICHOLS, Core Laboratories, Inc.

THE purpose of this paper is to present a contour map that shows the geographical variation in geothermal gradients in the Mid-Continent and Gulf Coast oil fields.

● **Introduction.** Frequently there arises the need for an estimation of the temperature to be expected at a predetermined depth in working with a wildcat or in deepening old production into zones that are relatively unknown. The study of geothermal gradients in oil fields has been made previously by many investigators. One of the pioneers in this work was C. E. Van Orstrand[1], who, as well as most of the other investigators, was primarily interested in the relation between temperature and depth in a given locality. Between 1921 and 1929, American Petroleum Institute Research Project No. 25 fostered a thorough study of earth temperatures.[2] R. W. French did some work in California, the results of which were published in 1939.[3] In most of these studies, an attempt was made to correlate temperatures in a rather localized area. This paper will show the results of an attempt to correlate temperature gradients over rather large portions of the Mid-Continent and Gulf Coast areas.

● **Method of obtaining data.** It has been found that for complete thermal equilibrium to be established in a well, the well must stand undisturbed for a period of several hours to several weeks, depending upon the way the well was produced prior to the shut-in period.

The data in this paper were obtained in conjunction with running pressures in wells or in taking samples of reservoir fluid. Glass maximum recording thermometers were used in all but a few instances. The wells had been shut in from one hour up to 10 or 12 days. Since the wells were normal producing wells, some of the shut-in times undoubtedly were insufficient for complete thermal equilibrium to have been established and the temperatures measured do not necessarily represent the temperature conditions that will be encountered in a well that is producing oil. The data, therefore, can be useful in working with or in estimating the temperatures to be expected in producing reservoirs.

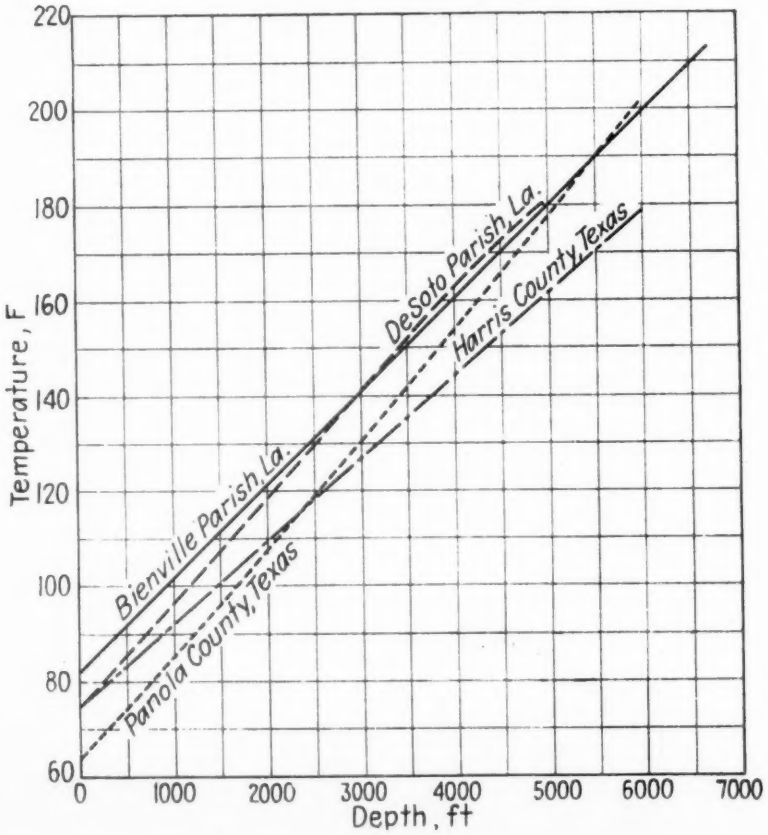
In obtaining a thermal gradient by dividing the difference in temperature of the formation and the mean annual surface temperature by the depth of the formation, one is assuming the depth-temperature line to be straight. Depth-temperature curves are almost straight lines (Fig. 1). On close examination of accurate data, however, a slight curvature usually is observed. Most wells yield curves with slopes increasing with increasing depth. These curves are believed to be from wells that are in and are underlain by sedimentary material. Some few curves have slopes that decrease with increasing depth. These curves are believed to be from wells that are underlain rather closely by granite or some other igneous rock. Most investigators have assumed a straight-line relation in calculating the thermal gradient because of the simplicity of calculating gradients from straight lines. In order to conform to the common method, the assumption of a straight-line relation has been used in this paper.

Approximately 1800 temperature measurements in 194 fields were used in this work. All individual measurements within a given pool were averaged and the averaged value was used in contouring. In many cases, several wells in a pool were measured. Also, many wells were measured several times over a period of years. There were other instances in which only one or two measurements were available for a pool.

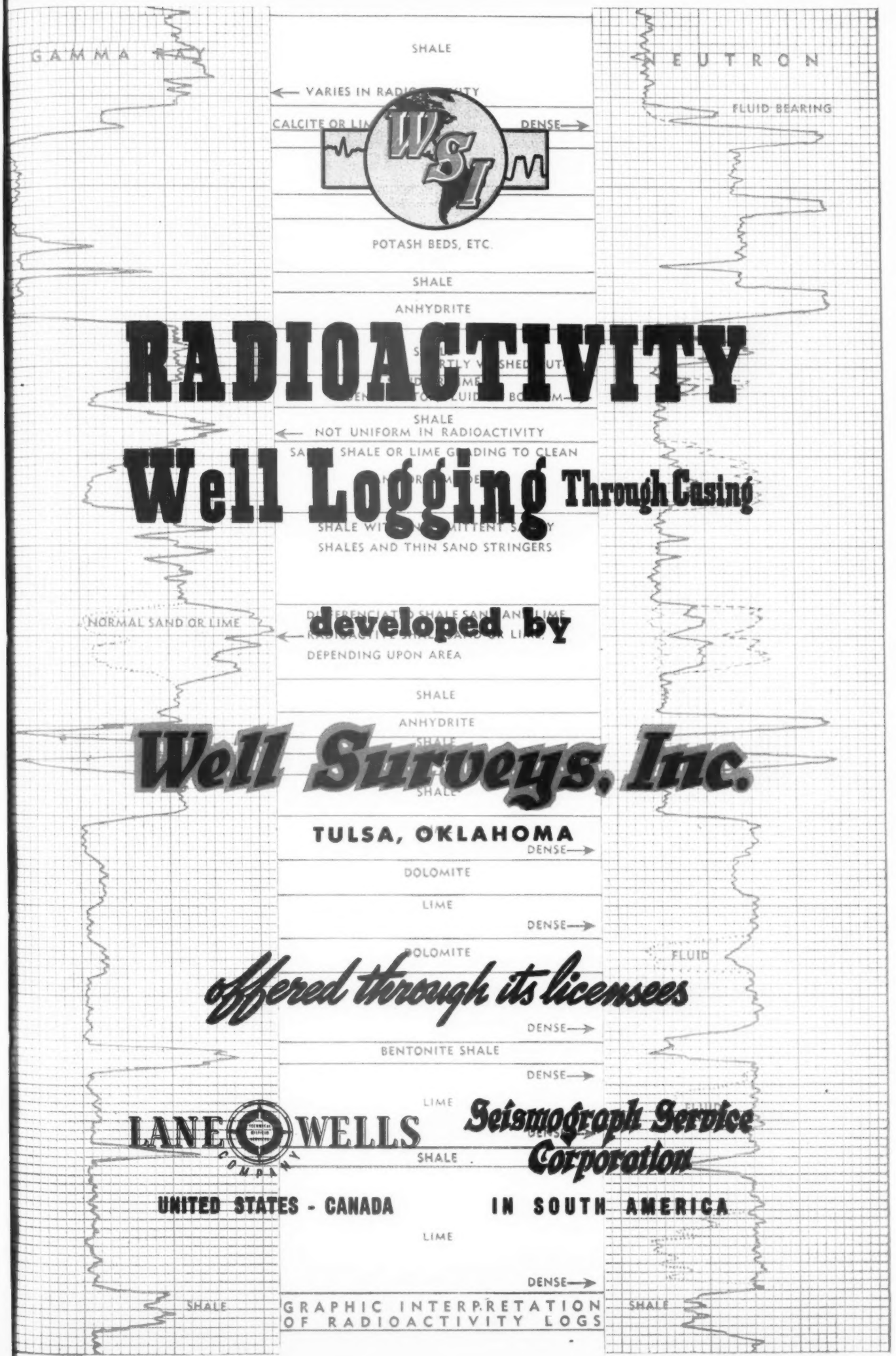
The average thermal gradient was plotted on the map in the proper geographical location for that particular pool. The contour lines were then drawn in the general area where sufficient points were available to warrant the interpretation presented. In many places there were too few points for accurate contouring. In these areas, either the lines were dotted or were omitted. The resulting map of geothermal gradients in oil fields is given in Fig. 2. In general, the contour interval is 0.1 F per 100 ft of depth, but where the contour lines are crowded intermediate lines were omitted.

The mean annual air temperatures measured and reported by the United State Weather Bureau for several cities in the areas under consideration are shown in Table 1. The numerical average of these values is 66 F. John A. McCutchin[4] states that "depth-temperature curves for wells in Oklahoma and Kansas intersect the temperature axis slightly above a point equivalent to the mean annual air temperature of the area where the well is located." The producing wells

FIG. 1. Temperature-depth traverses.



*Presented before American Institute of Mining and Metallurgical Engineers, Galveston, Texas, October 1946. Published in *Petroleum Technology*, November, 1946.



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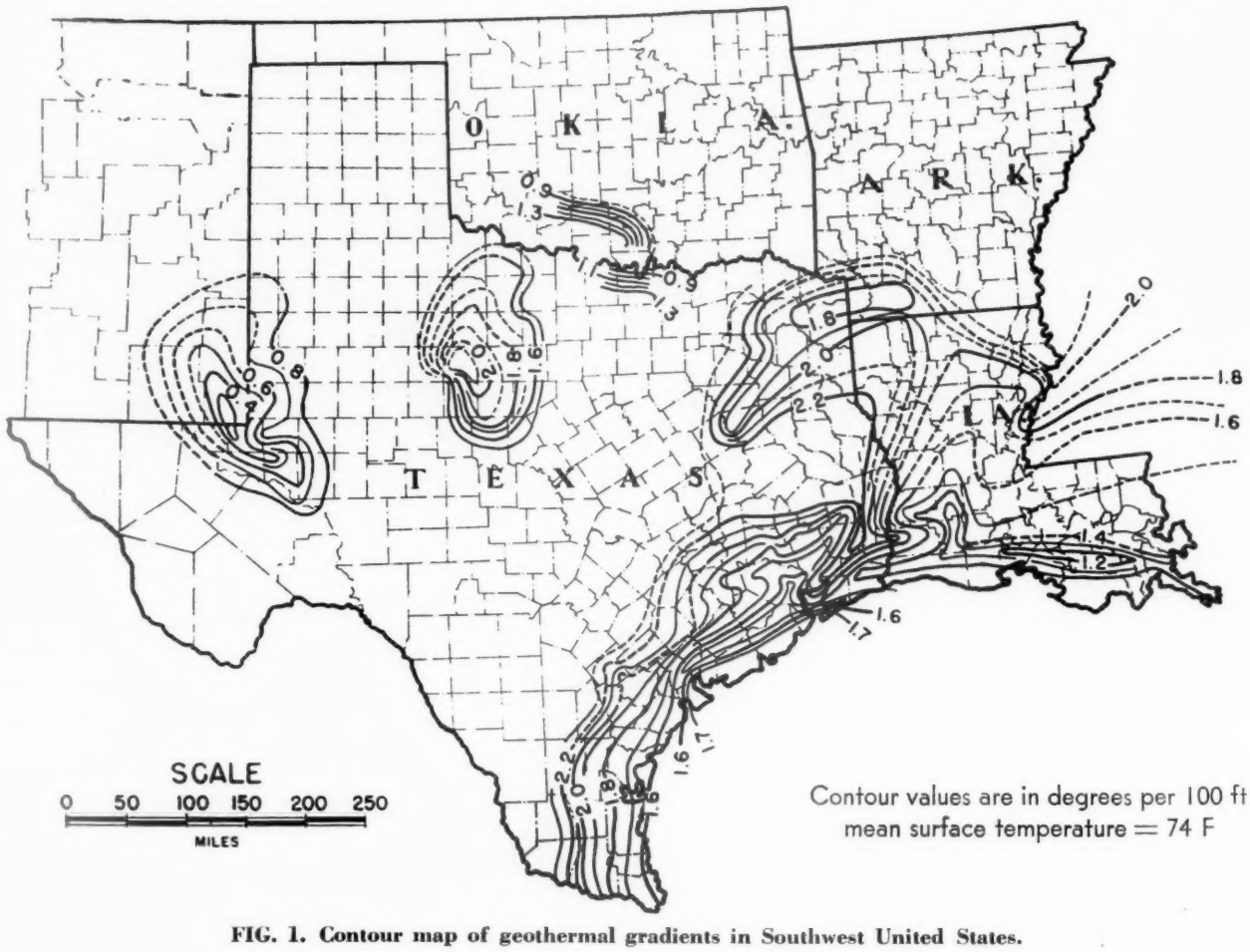

FIG. 1. Contour map of geothermal gradients in Southwest United States.

in which we have measured temperatures in the Mid-Continent and Gulf Coast areas have shown a tendency to intersect the temperature axis at the surface at or near 74 F. With these things in mind, a value of 74 F was chosen as the mean annual temperature to be used in conjunction with producing wells. This value was used in calculating the gradients in the paper, and as long as this same value is used in estimating temperatures with the contour map the resultant data will be reliable.

TABLE 1. Air temperatures reported by U. S. Weather Bureau.

Location		Mean annual air temperature, °F
City	State	
Dallas	Texas	65.7
Houston	Texas	69.2
Corpus Christi	Texas	69.1
Brownsville	Texas	73.1
Beaumont	Texas	69.2
Gainsville	Texas	64.2
Lindale	Texas	65.5
Lafayette	Louisiana	68.0
New Orleans	Louisiana	69.6
Shreveport	Louisiana	66.0
Ardmore	Oklahoma	63.1
Oklahoma City	Oklahoma	60.1
Average		66.2

● **Conclusions from contour map.** Certain conclusions may be drawn from Fig. 2 with greater or less assurance. It is apparent that the New Mexico-West Texas area is characterized by a low gradient basin that lies in a northwest-southeast direction. The gradients are considerably lower than those of the Gulf Coast area.

The contours along the Gulf Coast reveal several points of interest. In the general vicinity of Matagorda Bay a plateau of high temperatures appears with its axis just off shore and parallel to the shore. With the exception of this plateau, the temperature gradients elsewhere along the coast increase as one moves inland. The high-temperature plateau near Matagorda Bay and the increasing temperatures inland form a trough, which starts near Corpus Christi, runs in toward Yoakum, and finally moves back out toward the Gulf along the Mississippi Delta.

Just above the coast on the Texas-Louisiana boundary line, a rather rapid change in the temperature gradients is evident. This change culminates in a high plateau near Beaumont, Texas.

In the northeast Texas-Arkansas-Louisiana area, a large irregular basin was found in the general vicinity of the Sabine uplift. There were insufficient points to define the entire area, but a trend in southern Oklahoma seemed to be apparent in the Anadarko Basin.

● **Application of contour map.** The map may be used in estimating temperatures in the following manner:

Estimated temp., F.
= [Depth × Gradient from map] + 74 F.

In using the map, the following points should be considered. In the areas where the contour lines have been dotted, the number of control points were insufficient for accurately defining the position of the gradient lines, and they should be used with this in mind.

It is considered unwise to attempt to extrapolate the contour lines into areas that are not contoured on the map.

It should also be kept in mind that the data used in compiling this map were derived from producing wells. The data may be used for general purposes dealing with producing fields.

● **Acknowledgment.** The writer wishes to acknowledge the assistance given by Dr. F. C. Kelton, Mrs. Penelope Eades, and Mr. Ed Clark. He wishes also to acknowledge the data furnished by the Phillips Petroleum Company.

● **References.**

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★ ★ ★

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Drilling equipment records*

By MARK HART, Rowan Drilling Company

THE drilling contracting business has developed from small personal businesses to large corporations with millions of dollars invested. Gone are the days when the owner of a contracting firm slept under the boilers, directed all his work, and knew all his equipment, its condition and location.

The first theory adopted for practice by many a drilling contractor was that his office and all his office employes were non-productive or just a necessary evil. This practice required the very minimum of office space, a combination stenographer-bookkeeper, and a set of single entry books. This was overhead, a word that was spoken very quietly as a cost item.

In this great development of the drilling industry, we find that many contractors realized that their offices could be made into producing units, that the word "overhead" was a necessary indirect cost, and that the statistical information developed by his white collar employes was used not only in making bids, but also as a guide for field operations. This type of information was making him money before, during, and after the rotary stopped turning.

Although development has been rapid in cost accounting and general office practice in the last few years, there has been little effort devoted to the development of adequate equipment records. It is usually the weak spot in his accounts.

This can be attributed to the fact that these records are considered secondary to cost accounting. The contractor knows that he has the power, the pumps, the hoisting equipment, and other necessary major items to run his rig; and, if he does not have the smaller items with his rig, he can find them in the nearby supply store. The smaller contractor thinks that he has too few pieces of equipment to bother with records—he can remember each piece purchased. Then, part of the blame is laid to the often stated impossibility of getting field cooperation on transfers.

Little excuses can weigh heavily on the mind that does not understand the proper value of the item in question.

The sizeable investment alone should have prompted the development of the very best systems of records for protection against theft and loss. Most contractors operate over vast areas, and some have their huge investment scattered over three or four states. They find state income taxes, use taxes, and other state taxes, which are based on their investment in or value of their equipment.

Equipment records should not be considered as secondary to a contractor's cost accounting system. They are a part of this system, for his cost accounting should reflect the operating cost of his various major items of equipment.

Equipment records should assist in recording sales of equipment. Without the proper identification of equipment sold, it may be difficult to prove to the federal revenue agent that the profit made was from the sale of a capital asset. As the normal income tax rate is usually much higher, this point should certainly be considered.

In this discussion of equipment records, let us assume that you are a large drilling contractor or a small one with ambitions of growing and that you want your equipment record system established so that it may grow with you while you reap all benefits afforded the larger operators.

Complete equipment records will include drilling equipment, lease equipment, furniture and fixtures, and drill pipe—all tangible fixed asset accounts on your books. Although these records are subsidiary, they should be kept in balance with corresponding accounts on your books and made a part of your accounting system. This discussion, however, shall be confined to drilling equipment.

Under any record system on drilling equipment, it is necessary that the rigs be identified. It is usually done by numbers.

In posting invoices to the general ledger, each item of equipment charged to the drilling equipment account will be given an equipment record number (E. R. No.) and assigned to the rig for which it was purchased. The Equipment Record Sheet or Card (Fig. 1) will be made with a complete description that should include all distinguishing characteristics of the item purchased, the size, make, and serial number. Other pertinent information such as the supplier, invoice number, rig number, book reference, date of purchase, and cost are included in this permanent record.

So that this E. R. No. may be permanently associated with the equipment to which it is assigned, it is given to the toolpusher under whose supervision the equipment is to be used. He, then, will have the number stenciled or raised with a welding torch on the equipment so that is it branded for life with this number. It is then that the office and the field will have a common ground to know this piece of equipment.

This method certainly is appreciated by the field man, for the E. R. No. becomes the distinguishing characteristic, and from then on he can give little description of this item on his material transfers or yearly inventories.

In the office, the E. R. Sheets are arranged by rigs and warehouse yards with a control sheet, usually of a different color, in front of each group. The control or tabulation sheet will reflect the purchase or transfer date, the E. R. No., a brief description of the equipment, and will be lined for a debit, credit, and balance column. This information forms a quick reference sheet, as well as a control, for finding the record on a certain piece of equipment when the rig number is known. The combined cost reflected by the sheets under any one rig should agree with the balance on its control sheet, and the combined totals of the controls will balance with the drilling equipment accounts on the general ledger.

This system affords a perpetual inventory of all drilling equipment. It tells you what you own and where it is located.

The Maintenance Record (Fig. 2) can be posted from your cost accounting system. It may not be used on each item of equipment, but it has been found very useful in comparing competitive equipment or for keeping check on the operating cost of major items, such as engines, drawworks, pumps, swivels, and rotaries.

These items are all listed as sub-divisions under "Well Cost Extension Chart —Contract Drilling Expense—Rotary" on page 81 of your Manual of Uniform Accounting Practices. This extended distribution of well drilling cost is practiced by many contractors whether or not they maintain equipment records.

The Material Transfer (Fig. 3) which is necessary in keeping any perpetual inventory, is the key to this entire system. Every time a piece of equipment is moved to another rig or into the yard, a transfer must be made with one exception. The one exception is when an entire rig is stacked in the yard. Every time a piece of equipment moves, some one must be responsible for this move. If the rig is stacked when the equipment is taken off, then it is the duty of the person authorizing the transfer to send the office a material transfer. So long as there is a toolpusher assigned to a rig, it should be his duty to make the material transfer on all equipment leaving his rig. This should be a company policy, understood by all.

The importance of these transfers can be impressed on the mind of the toolpusher by explaining to him that he is responsible for every one of your dollars represented in the equipment on his rig or rigs and that he is being held accountable. If equipment leaves his rig, the only way he can be relieved of the re-

*First published in *The Drilling Contractor* for August 15, 1946.

sponsibility is to make out and send in a material transfer.

In order to enforce the rules governing this system and to check for loss of equipment, it is necessary to take physical inventory of each rig and warehouse annually and check inventories against the control sheets. All discrepancies should be corrected. A list of such discrepancies with offenders might be presented to the owner or officer who may wish to approach an offending toolpusher, John Banks, with:

"John, your inventory was short $12,950.00."

John is immediately on the defensive. He will long remember that statement even though you do tell him later that he failed to transfer an S. & B. G-450 power pump from his rig. He may begin to think of your equipment in terms of dollars.

All reference systems are made more effective by cross references. This equipment record system is no exception. The Unit Equipment Record (Fig. 4) carries only a brief description of the item, but has all references identical to the same E. R. No. in the master system by rigs. The E. R. Nos. are kept in numerical order, which will automatically line them in the order of purchase or book entry. By using labeled dividers every 100 cards this is a quick reference when only the item and E. R. No. is known. This situation occurs when an item is transferred at least twice between the inventory periods and the first toolpusher failed to send in a material transfer. This file, then also helps to correct errors by the field men even before the annual inventory is taken. The office clerks will find it very handy in finding items when they are given only the name and about the time of purchase.

Material transfers will be posted to both the master file by rigs and the numerical file. All postings to the master file will be made on the controls only and the E. R. Sheets will be transferred. The transfer is merely recorded on the proper card in the numerical file and each card will remain in order.

It must be definitely understood that only capital items on the books are to have E. R. Nos. Controls on the smaller expendable items would require more detail than such records would be worth.

Equipment records with controls by rigs and warehouse yards will reflect the capital investment in each rig at all times. The value of controls on equipment in various yards is derived from the fact that they provide a ready index to available items of equipment that may be needed in another area. Knowledge of this availability will prevent unnecessary duplicate purchases, possibly of a seldom used item, and will expedite delivery to a rig where it is badly needed.

When the supply line is thin, and the demand is doubled, as in war years, the immediate finding of a piece of equipment in your own back yard from your warehouse yard control sheet would certainly be lucrative to the contractor especially when that item will terminate a costly shutdown. ★ ★ ★

FIG. 1.

EQUIPMENT RECORD — COMPANY E.R.NO. 791

NAME & DESCRIPTION: TYPE G-540 S. & B. POWER PUMP COMPLETE WITH SHORT SKIDS

SIZE: 7-3/4" x 20" — NO. PCS.: 1

DATE ACQD.: 4-2-45 — 2ND HAND / NEW — MFGRS. NO.: G-2162 — INVOICE NO.: 21081

LOCATION: Rig No. 2 — VOUCHER NO.: 500 - Apr.

PURCHASED FROM: S. & B. Tool Co., Inc. — UNIT COST: 12,000.00 — TOTAL $: 12,000.00

ADDITIONS: FROM: S. & B. Tool Co., Inc. — REF.: 20 M — COST: 950.00 — TOTAL $: 12,950.00

COST: — TOTAL $:

COST: — TOTAL $:

COST: — TOTAL $:

Extend skids to accomodate 1 - 400 H.P. Electric Motor

FIG. 2.

MAINTENANCE RECORD — COMPANY E.R.NO. 791

CONTRACT NO.	FOOTAGE DRILLED	MEMO	NO. DAYS	AMOUNT	DATE	TOTAL EXPENSE
870	8,900'	Rig 2 Nichols No. 2	101	1,261.83	9-1-45	1,261.83
892	8,750'	Rig 2 Snyder No. 4	89	892.31	1-2-46	2,154.14
901	8,561'	Rig 2 Anderson No. 8	85	1,053.50	4-20-46	3,207.64
926		Rig 4 Brants No. 1				

FIG. 3.

If Drill Pipe? String No.
If Drill Collar? No.
If Equipment? E. R. No. 791

Material Transfer — No. 466

Odessa District April 20 1946

CHARGE B. L. Brants #1 Rig No. 4 Job No. Acct. No. $

CREDIT D. C Anderson #8 Rig No. 2 Job No. Acct. No. $

Description of material or equipment transferred and condition.
(On material, state whether new, or if second hand, whether 1st, 2nd or 3rd class)

1 - G-540 S & B Pump

To be used for Mud mixing during fishing job.

Person Receiving — John Banks, Drilling Supt. or Warehouseman

FORM 15- 45 BOOKS 11-44 PATTON PUB. CO.

FIG. 4

UNIT EQUIPMENT RECORD

SUPPLIER: S. & B. Tool Co., Inc. — V.O. No.: 500 — Mo.: April — 19 45 — E.R.: 791

EQUIPMENT: G-540 Power Pump — UNIT COST: 12,950.00

ADDITIONS	FROM	V.O.-M.T. NO.	MONTH	YEAR	COST	CUMULATIVE TOTAL

ASSIGNED TO: Rig No. 2

TRANSFERRED FROM	TRANSFERED TO	M.T. NO.	MONTH	YEAR	BY
Rig No. 2	Rig No. 4	466	April	'46	Banks

FORM NO. 00 00 0-00 PATTON

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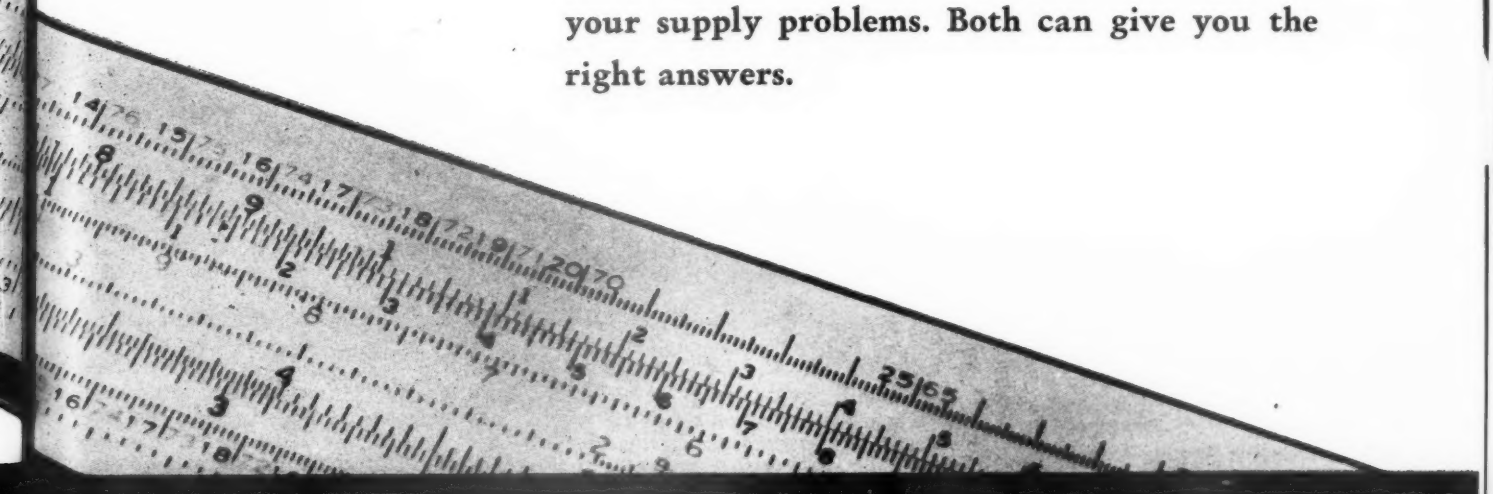

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Deep cable tool drilling in Appalachian area*

By HAROLD W. HAUPT, *Vice President*, Acme Drilling Company

IT GIVES me great pleasure to present this paper, on deep cable tool drilling, based on actual experience derived from the drilling of a number of deep holes in the New York State, Pennsylvania, and West Virginia areas.

This type of drilling is satisfactory and has been carried on with a considerable amount of success in the Appalachian area in the last 20 years, but with increasing efficiency in the last few years, due to new methods and improvements in cable tool drilling.

The deep cable tool drilling in the Appalachian area is to a very large degree carried on by contract and there are a large number of independent contractors who do this work. They, together with the skilled drilling crews, improved materials and new practices in meeting adverse drilling conditions, improvements in pipe, development of derricks to handle long strings of casing, improvement in wire lines and all drilling machinery, have combined to make possible and carry on deep cable tool drilling successfully.

Deep drilling is carried on in this area in search for natural gas and oil and at present is at depths ranging from 5000 ft to 10,000 ft. Such drilling is usually done on structures known as anticlines. The deeper formations in these anticlinal areas are very treacherous, because of faults, cross-faults, slips, steep slopes, gas pockets, and other adverse conditions.

The casing schedules of the deep holes drilled in this area with the Oriskany as the objective horizon, are usually set up so that a string of 7-in. OD casing can be set in the Onendaga limestone formation, which lies on top of the chert and Oriskany sandstone formation. If gas is found in the Oriskany the well can be produced through the 7-in. OD casing. To arrive at this casing point, which is beneficial to the producer from an operating standpoint and beneficial to the contractor as a protection against fishing jobs, it is necessary to use the pipe schedules, consisting of 50 ft to 100 ft of 16-in. to 20-in. casing; 500 ft to 800 ft of 13-in. to 16-in. casing; 800 ft to 1500 ft of 10-in. to 13-in. casing; 2000 ft to 4000 ft of 8⅝-in. to 10-in. casing; 6000 ft to 8000 ft of 7-in. OD casing, depending upon the locality and the proposed depth of the well.

In drilling a deep hole in this section, there is very little difficulty encountered in the top formations, with the exception of the usual small number of minor fishing jobs. The upper formations usually consist mostly of sandstones and limestones and take considerable time to drill because of the hardness of the formations and the large hole sizes. The fishing jobs in these formations are caused by the hardness of the formations, which has a destructive effect on tool joints, by settling sands, by caves caused by water, and by faulty materials.

The lower formations are considerably different in many ways. They usually consist of limestone and shale, with shale predominating. The drilling in this section of the hole is not hard ordinarily, but is hazardous due to caving conditions, gas pockets, and abnormal structural conditions. This section consequently takes considerable time to drill.

In the past a caving hole was one of the most difficult situations encountered but due to new developments in controlling caving formations with cement and a plastic material called drilling compound, a large part of this trouble has been eliminated. These developments also have eliminated excessively large holes and decreased the number of casing strings. We have been able to make much better completion time with these new developments, by means of better progress in rate of drilling and fewer fishing jobs caused by caving formations above the actual drilling point or the bottom of the hole. Caving from above the working point is a dangerous thing in a drilling operation. It not only causes delay in the drilling, but causes a good many fishing jobs, which in turn take considerable time and cost considerable money, because under a thousand feet of cavings from this type of formation a fishing job is difficult and costly. After losing a string of tools under these conditions, one may be a month or more reaching the top of his tools. This is an expensive proposition; however, by the use of drilling compound and cementing techniques we have been able to eliminate a large part of this type of trouble.

There remains a caving condition that we have not been able to eliminate up to the present time without the use of cement, and that is a caving hole at the bottom or at the point where the tools are actually working. This caving condition is usually the result of unstable or "broken" formations. Correction of this condition also takes considerable time, but in most cases is not too serious and can be carried on successfully. After the hole is drilled through the caving section it can be controlled with little trouble by the use of drilling compound. In some sections of this area, if the well is located on a less complicated part of the anticline, we have little trouble from caving, and the well can be handled easily and satisfactorily without cementing or the use of drilling compound.

One of the most difficult problems in deep cable tool drilling has been, and still is, the development of crooked holes, that is, the hole going off vertical as much as 15 to 20 deg. This trouble is caused by slips and faults in the formation; however, in most cases, the well is drilled to a point to where the operator is satisfied that the possibility of getting a producing well is nil, even if the hole is off as much as 15 to 20 deg. Crooked holes can be straightened successfully to a point to where the hole can be continued on by means of new methods or new tools for this purpose, and, in some cases, by shooting with nitroglycerin.

"Deviation" in the hole is caused by sloping or hanging formation, or by crossing through a fault. This condition is one of the most difficult problems of the cable tool drilling method. Up to the present time we have been able to drill a hole under this condition to a point where the operator is satisfied. By means of new developments in tools, such as spiral star bits, hillside bits, allowing the hole to cave and shooting out a section to allow the tools a chance to run at a more vertical position, cable tool drilling has been able to carry on a fairly successful technique through these bad formations.

Another problem in deep cable tool drilling is the penetration into high-pressure gas pockets. These are usually found in the deeper and more broken formations. These pockets are dangerous and quite frequently cause serious fishing jobs. While drilling in an anticipated gas pocket formation, the contractors usually continue with the hole in the following manner: Pilot ahead 40 to 50 ft with smaller diameter tools, thus allowing the sudden burst of pressure from a gas pocket to pass the tools at the immediate larger hole above. After proceeding in this manner 40 to 50 ft, we then come back up the hole to a point where we started the smaller diameter hole and ream the hole down to the bottom and continue on with this sequence of procedure until such time that we think we are through that kind of formation. Another method used with a certain amount of success by some contractors is to carry a thousand feet or more of salt water at the bottom of the hole. This practice eliminates and more or less neutralizes some of the high pressure and the sudden shock from the gas pocket blowout by the use of the hydrostatic pressure of the water, which acts something in the order of a cushion effect to such an explosion.

Fishing jobs caused by gas pockets usually are difficult and costly. In most cases the tools are blown past the cable thus fouling the cable and the tools. The

*Presented at Spring Meeting, Eastern District A.P.I. Division of Production, Pittsburgh, Pennsylvania, June 13-14, 1946.

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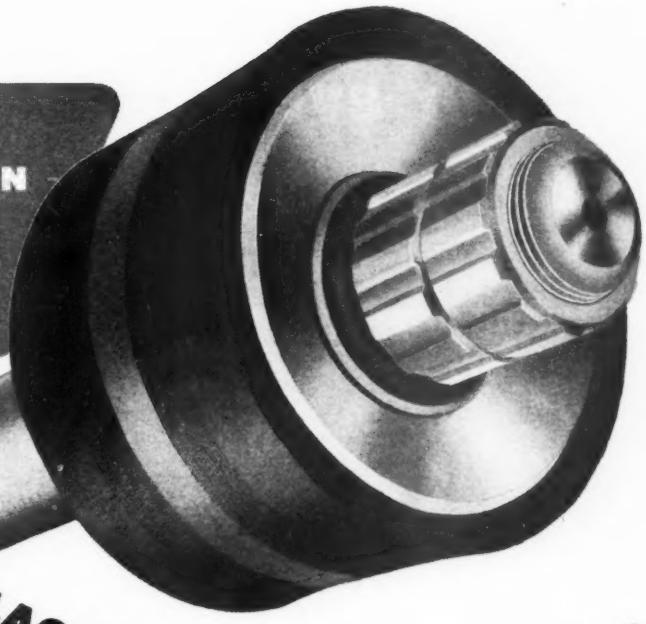

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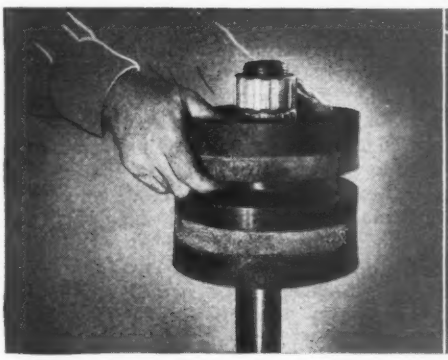

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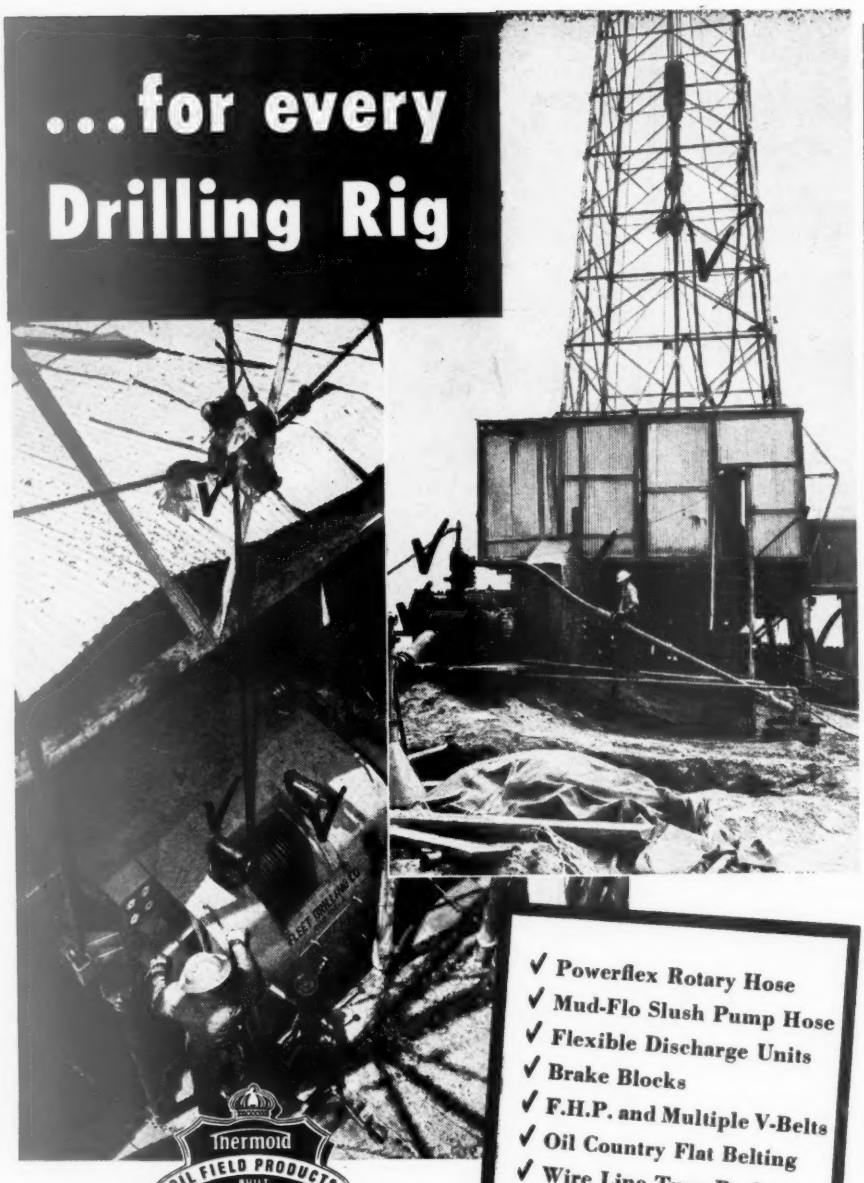

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corrective procedure then is to whip the line off at a kink or dogleg in the line caused by the blowup or cut the line at the closest point possible to the tools, then fish out the wire and tools. If the tools are not loose, drill by them and if this does not loosen the tools cement them in and continue on with the hole. The last mentioned operation has been done successfully in many cases. In some instances there were as high as two or three strings of tools left in the hole by this method; and so, even with these problems and difficulties, we were able to proceed to the casing point and run the size pipe intended.

Despite all the difficulties mentioned the cost of deep cable tool drilling is comparatively low, as will be shown by the following figures, which are actual average costs to the operator of 14 deep wells drilled in the Appalachian area, exclusive of casing, to the average depths indicated:

6000 ft to 7000 ft, $6.50 to $7.00 per ft.
Below 7000 ft, $7.00 to $9.00 per ft.

The foregoing costs depend largely upon the locality in which the wells are drilled and also upon the difficulties encountered as heretofore mentioned.

All the foregoing practices and improvements combined have enabled the contractor and operator to carry on a deep cable tool drilling operation to depths as high as 10,096 ft in the Appalachian area successfully and at a minimum cost. ★★★

Pipe and tubing

The current demand for tubular products is difficult to estimate accurately in total, as pipe is primarily a service item. In February of this year we conducted a spot survey among the large oil and gas companies, covering pipe lines 20 in. o.d. and larger which they had on order or desired to install within the next 5 years. The aggregate of this tonnage represented over 1 million tons a year, which is 20 times the volume of this size pipe purchased for trunk lines in the 5-year prewar period. This high ratio of demand to supply is significant for this commodity only, as the 20-in. and larger trunk line tonnage in the prewar period was only 2 per cent of the total pipe and tubing tonnage.

Let us examine the over-all trunk line demand, including all sizes of pipe, which represented about 10 per cent of the total prewar tubular tonnage.

The demands for refinery pipe and tubing for maintenance and new construction were checked in a brief survey, and the requirements were about 7 times the prewar period purchases.

While the supply of oil country goods does not equal the present demand, it is much more nearly in balance than the situation existing with respect to line pipe and refinery tubular goods.

In the case of standard pipe and miscellaneous line pipe, the market is so scattered and varied that it would be difficult to conduct a survey of demand.

Taken from "Availability of Pipe and Tubing," presented by W. F. McConnor, vice president in charge of sales, National Tube Company, before National Association of Purchasing Agents, New York, June 2, 1947.

Deep rotary drilling applied to Appalachians*

By BRUCE R. MILLER, The Ohio Oil Company

● **Introduction.** The desire to improve performance and results obtained in drilling hard abrasive sands, dense shales, and siltstones of the deeper Appalachian sections has influenced a number of operators to use rotary equipment. The adaptation of rotary equipment to drilling in this section must take into account properly conditioned mud, rigs adequately powered, completion practices, drill pipe wear, rock bit footage, and well control. Day work contracts have placed contractors under restraints and partially removed the incentive to improve performance. These factors with high freight charges for moving rigs, repairs, and supplies great distances have made rotary drilling costs high. Rotary drilling has provided such desirable benefits as:

1. Conservation of reservoir pressures.
2. Complete control while drilling and completing.
3. Selective and multiple completions.
4. Saving in casing.
5. Hole size maintained to objective.
6. Reduced drilling time.
7. Eliminate hazards of blowouts and fires.
8. Provide data for reservoir study.

Expanded use of rotary equipment for deep well drilling in the Appalachian area is indicated and such use will result in a continued decrease in the cost of drilling by the rotary method.

The scope of this paper is limited to a discussion of rotary drilling methods and procedures employed in drilling the deeper horizons of the Appalachian area with observations and suggestions to improve its performance.

Cable tools have for some time been used extensively in the Appalachian area with varying degrees of success and are used in some instances in this paper as a basis for comparison with results obtained with rotary tools.

● **Rig selection.** In the selection of the equipment and the contractor for drilling a deep well in the Appalachian area a number of items should be carefully considered. These items may be enumerated as follows:

1. *Size of rig.* The rig should be sufficiently large to make good time in tripping the drill pipe without placing undue overload on drawworks, clutch, transmission, chains, and motors. If the rig is powered by gasoline or natural gas engines the 10 per cent reduction in power that may be developed by these engines at altitudes of 3000 ft or better must be considered. A satisfactory rule of thumb regarding horsepower requirements in the Appalachian area is 1000 hp for depths below 8000 ft.

2. *Versatility of rig.* The rotation speed of drill pipe and the pump pressure developed should not be limited one by the other. Some of the Appalachian section requires relatively high rotary speeds and pump pressures, whereas other sections require low rotary speeds and high pump pressures. This may be illustrated by tests conducted while drilling the Devonian shale section. Increasing the rotary speed from 65 to 80 rpm and the pump pressure from 750 to 1000 psi increased the rate of penetration by 20 per cent. The higher pump pressure and increased rotary speeds could not be maintained for any appreciable length of time as severe overloading of engines resulted. If mechanical failure occurs, the rig under ordinary circumstances should be capable of continued operation until replacement parts can be procured.

3. *Availability of repairs.* The selection of power rigs for operations in this area insofar as possible should be confined to equipment, and in particular motors and engines, for which replacement parts may be obtained with a minimum of delay.

4. *Supervision.* Supervision, always an important role in any undertaking is doubly important for operations in the Appalachian region. The needs of all supplies such as mud, cement, bits, coreheads, reamers, fishing tools, and various oil-field services must be anticipated and arrangements made far in advance of their actual need. Much of the above equipment and service must come from Texas, California, Oklahoma, Illinois, and other states quite distant from the Appalachian area. The supervisor and tool pushers for the Appalachian area should be thoroughly familiar with operations in hard rock country as well as operations in a locality where lower temperatures and adverse weather conditions are to be encountered.

5. *Operating personnel.* Crews should be selected that are accustomed to working under adverse conditions and low temperatures. It is a distinct advantage to have crews that have previously worked on the rig and as far as possible from the same section of the country. Rigging up technique and procedure varies widely in the various sections of the country and creates much confusion and lost time when the crews are not accustomed to rigging up and maintaining various sections of the rig in the same manner.

● **Drill pipe.** Drill pipe wear in the Appalachian area compares quite favorably with that obtained in drilling other hard rock sections such as encountered in the Rocky Mountain area. Under ordinary circumstances drill pipe may be expected to drill 50,000 ft of hole. Drill pipe wear has been found to be greatly accelerated in that portion of any hole that has been drilled by cable tools. This accelerated wear may be attributed to the irregular walls of the hole and the absence of filter cake to cushion and lubricate the drill pipe. Figs. 1 and 2 show two straight hole surveys of wells that were partially drilled with cable tools. The course of the hole shown in Fig. 1 was drilled with cable tools to a depth of 3900 ft and from that point was drilled to completion with rotary tools. The course of the hole, as shown in Fig. 2, was drilled to 7800 ft with cable tools and completed with rotary. These two surveys have one characteristic in common, the section drilled with cable tools in both instances spiral in a counterclockwise direction. Drill pipe wear is materially increased by the rotation of drill pipe in a conventional clockwise direction through these counterclockwise spirals that the cable tool hole has assumed. If cable tools are to be used to start holes that are later to be completed by rotary it is essential that the hole be straight and the need of some study on the influencing factor resulting in a counterclockwise spiral of the cable tool hole is indicated. The torque in the drill pipe when rotating in holes such as illustrated in Figs. 1 and 2 is much increased as compared with holes drilled by rotary regardless of the fact that the rotary hole may in some instances assume a course as far from vertical as that of the cable tool hole. The drag of a cable tool hole on drill pipe frequently increases the torque when the drill pipe is rotated sufficiently to make up the kelly when the rotary clutch is disengaged after rotating the kelly sub out of the tool joint box. This drag on the drill pipe has been noted to produce a differential on the weight indicator of 20 points between the weight of the pipe hanging in the hole and the weight when hoisting or lowering the drill pipe; in other words, a total of 135,180 lb difference between the line tension required to hoist or lower the drill pipe. Such a differential makes it very difficult to fish, core, or control accurately the weight on the bit.

Four and one-half inch, Grade D, 16.6-lb drill pipe with full hole tool joints has been found quite satisfactory for drilling the hole for the production string. Once the production string has been set, 3½-in. drill pipe should be utilized in preference to tubing if additional hole is to be drilled or cored. Although wells have been deepened and cored in the Appalachian area by utilizing 2½-in., 6.5-lb, 8-Rd. thread, J-55 tubing the reduction in the rate of penetration with tubing resulting from the necessity of carrying less weight on the bit and the increased time consumed in making trips makes it uneconomical as compared with the serv-

*Presented at Spring Meeting of the Eastern District American Petroleum Institute Division of Production, Pittsburgh, Pennsylvania, June 13-14, 1946.

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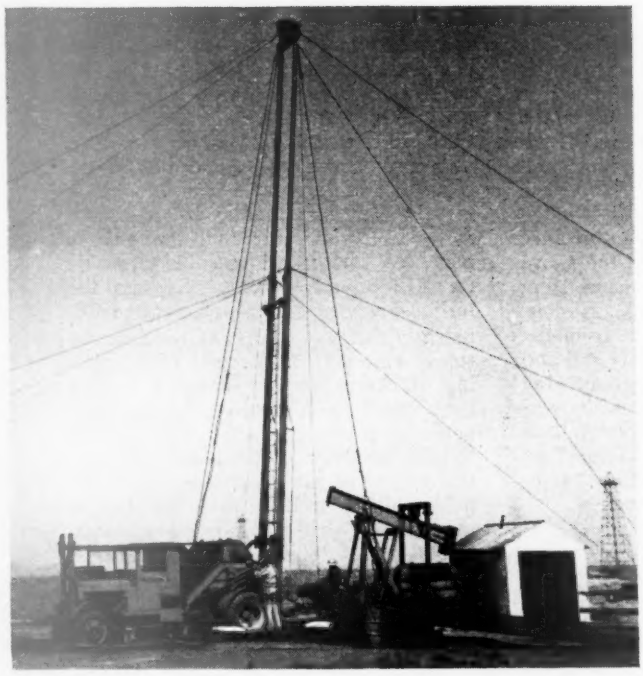
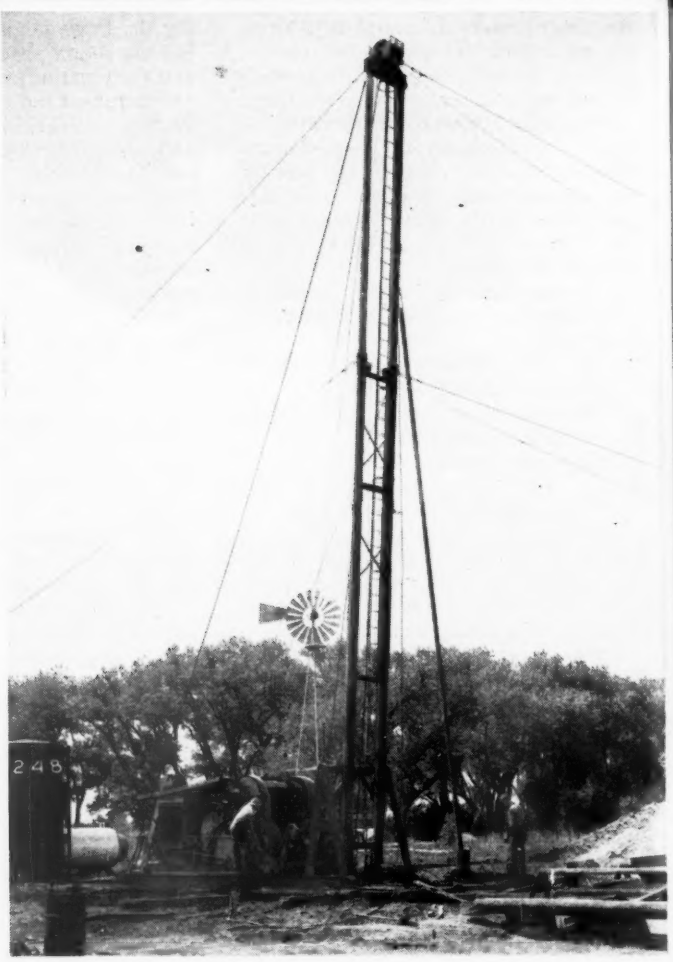


Double drum Mobilhoist with 55-foot double leg telescoping mast pulling 4,000 feet of rods and tubing. 48- or 55-foot single leg telescoping mast available.



Model R double drum hoist with spudder and 65-foot telescoping drilling mast. Complete rig is capable of drilling to 7,500 feet with cable tools. When Model R is equipped with rotary assembly, the same mast may be used for rotary drilling to 5,000 feet, or workover jobs to 6,000.

CONDENSED SPECIFICATIONS

Model	*Type of Mast*	*Available For Model*	*Load Safety Factor 2*	*Groove Sheave Dia.*	*Telescoped Length*	*Net Weight*
OLKBM	48-foot single leg servicing mast with cross sheaves and catline block as illustrated.	Q, H, K, Mobilhoist	38,600	16"	29' - 3"	2,700
OLKJM	48-foot single leg servicing mast with three sheaves in line and catline block.	Q, H, K, Mobilhoist	72,500	16"	27' - 8"	2,700
OLMJM	55-foot single leg servicing mast with three sheaves in line and catline block.	Q, H, K, Mobilhoist	58,750	16"	31' - 2"	2,900
TLMJM	55-foot double leg servicing mast, three-sheave crown and catline block.	H, K, S, Mobilhoist	79,500	16"	33' - 8"	5,100
TLDPM	65-foot double leg drilling mast, four-sheave crown.	H, K, R, S	128,000	20"	38' - 2"	7,200

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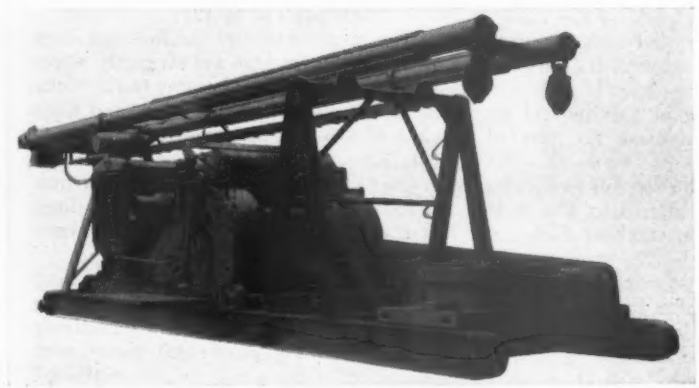
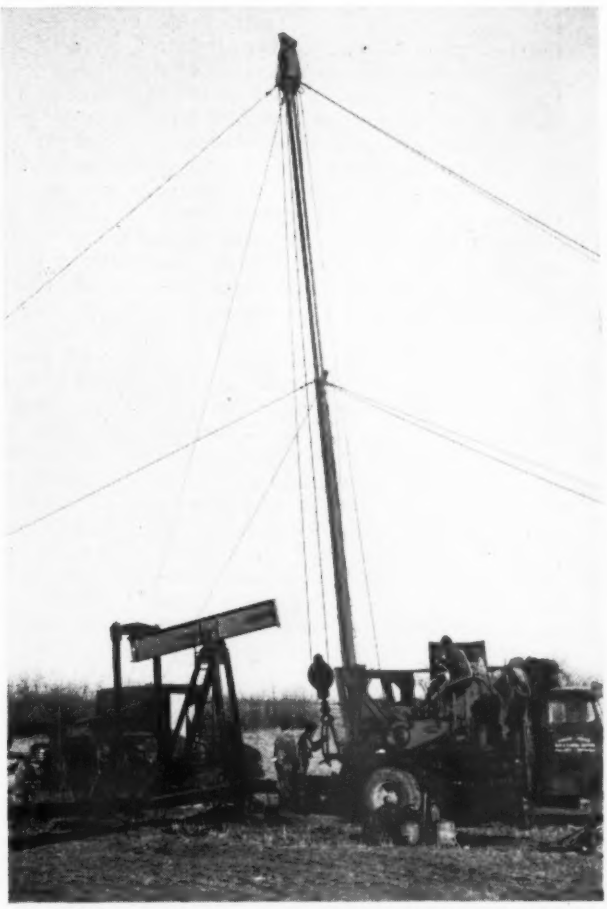


Model S hoist with 65-foot double leg mast, subframe and rotary table. Rig is capable of handling rotary workover jobs to 6,000 feet.



Model H single drum servicing hoist with 48-foot telescoping mast. Cross sheave crown permits block to travel three feet higher than when sheaves are mounted in line. 48- or 55-foot masts are available with cross sheave crown or with three sheaves mounted in line. Mast can be easily removed for derrick operations. Hoist is shown pulling rods and tubing from 3,910-foot well.

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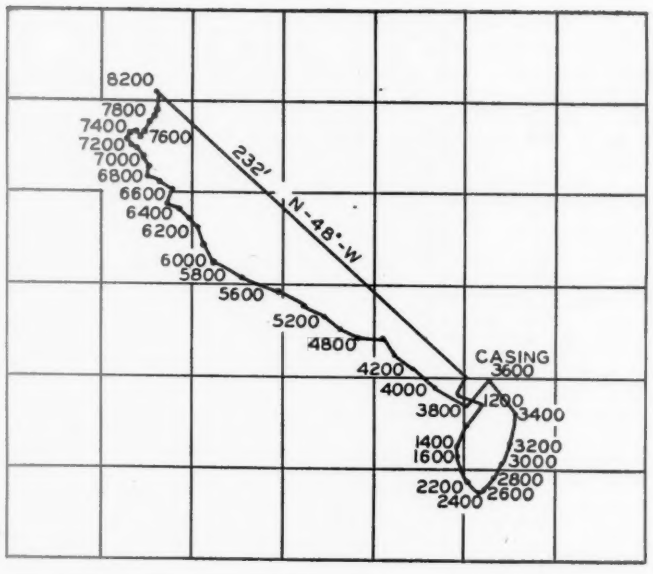

FIG. 1

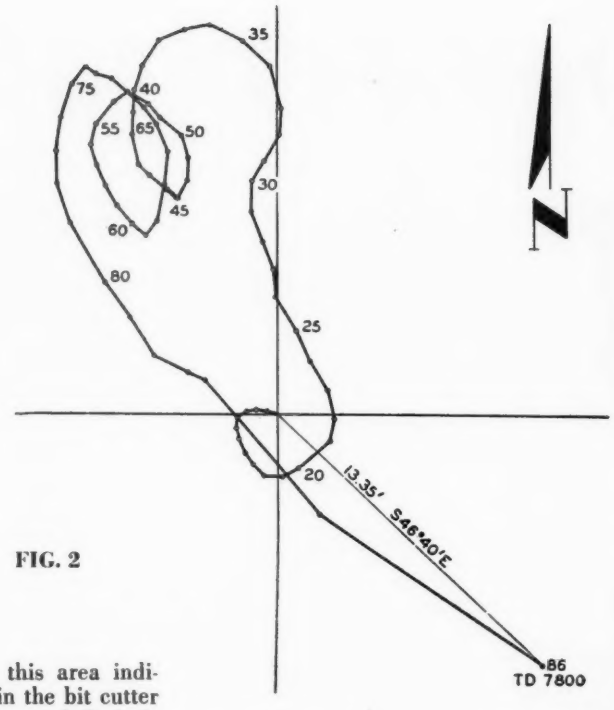

FIG. 2

ice of 3½-in. drill pipe. If any appreciable amount of hole is to be made below the production string, rubber or synthetic stabilizers should be installed on the drill pipe to prevent extensive wear of the production string and drill pipe by continued and prolonged rotation of the tubing or drill pipe.

Tool joint wear is high through the very abrasive sand sections of the Appalachian area and 4½-in. tool joints with an OD of 6-in. or 6¼-in. prolongs the useful life of the joints prior to resleeving or building up, by approximately 25 per cent, and the use of such joints is economically desirable and practicable. Tool joints should be calipered regularly and laid down before wear has progressed far enough to make it impossible to true up the OD of the joint at 5-3/16-in. Large numbers of stabilizers have been utilized on the drill pipe in open hole to minimize the wear on tool joints and drill pipe, however, the short life of these stabilizers when used in the open hole and subsequent cost of continued renewal of the stabilizers leaves the advisability of such practice open to debate.

The rate of penetration has been found more satisfactory when five or more drill collars are employed. These drill collars should have an OD as large as can safely be fished for in the size hole being drilled. It is important that sufficient drill collars be run to keep the drill pipe from whipping the walls of the hole and eliminate the necessity of using any of the drill pipe weight on the bit. Machine shops with equipment large enough to recut threads on drill collars may be quite distant from the well location and at least four extra drill collars should be available on the rig at all times. Bit reamers where employed have given excellent results in keeping the hole to gauge and increasing the footage obtained per bit by eliminating the necessity of reaming down with a new bit.

● **Bits.** Rotary drilling in the Appalachian area is accomplished by the use of rock bits exclusively. The selection of the tooth design of the rock bits used varies with the formation encountered. Experience obtained in this area indicates that improvement in the bit cutter bearings is desirable. As a whole it is considered economical to pull bits when the rate of penetration has fallen to one-half the rate obtained with a new bit. The 50 per cent reduced penetration figure is an average figure for the entire hole, and bits may be pulled sooner on hole near the surface due to the short period of time lost in making a trip. Such practice is economically desirable and should be encouraged. Inspection of bits when pulled indicates cutters to be in fair condition and suitable for continued running, however, in all cases the bearings are worn sufficiently to allow the bit to dig a tight hole. The penetration figures given above may be used as a rough guide, however, in some sections of the Devonian shale it has been found that the rate of penetration is increased once the wire edge has been worn off the bit cutter teeth. Data gathered indicate that a bit with long teeth on the cutter, such as the conventional rock bit used for drilling shale, but with the ends of the teeth flat similar to rock bits used in very hard formation or for drilling on junk iron, would increase the rate of penetration.

The selection of the size bit to use deserves considerable attention. The hole drilled should be the smallest that will provide sufficient clearance to avoid sticking the drill pipe or casing and allow sufficient clearance for the purpose of fishing. The reduction in hole size should not be carried to extremes as the bearings of larger bits will take more weight for a longer period of time as compared with smaller bits. A reduction in bit size from 12¼ in. to 10⅝ in. or 1.525 in. in diam will increase the rate of penetration by 14 per cent without a reduction in footage drilled per bit. A total of 100 bits should be required to drill the average 8000-ft hole with an elapsed time for drilling of 160 to 180 days.

● **Mud.** Mud for rotary drilling in the Appalachian area as a whole has not been given sufficient attention. Rotary mud has not been conditioned or tailored to the particular formations of the sections penetrated in deep Appalachian wells and this, no doubt, has influenced some operators to condemn rotary drilling in this area as dangerous and impracticable. The requirements of a mud satisfactory for drilling the Appalachian section may be enumerated as follows:

1. Low water loss (below 6 cc for a full 30-min test).
2. Relatively high gel strength (10 min gel of 4 to 5).
3. Low weight (10 to 10.5 lb per gal).
4. Low viscosity (45 to 50 centipoise).
5. Low sand content (below 10 per cent).
6. Thin filter cake (2/32 in.).
7. High pH (11 to 12).

The muds made by the hole are high in weight, have zero gel strength, water loss of about 15 cc, viscosity in the vicinity of 60 centipoise, pH of 8, and filter cake of 3/32 in. Chemicals and water to condition the mud should be added slowly and for this purpose steel drums placed on top of the return mud ditch and equipped with small valves have proved very satisfactory.

Steel mud tanks for handling mud offer many advantages over the old open earthen mud pits. It is conservatively estimated that a savings of 20 tons of mud on an 8000-ft hole may be accomplished by the service of steel mud tanks. The ability to exclude surface water from the mud reduces mud treatment from a continuous operation to treatment once in 8 to 24 hr, depending upon the size hole being drilled and the rate of penetration. Steel mud tanks provided with flooded pump suction eliminates the 10 per cent reduced mud pump efficiency experienced when pumps operating at high

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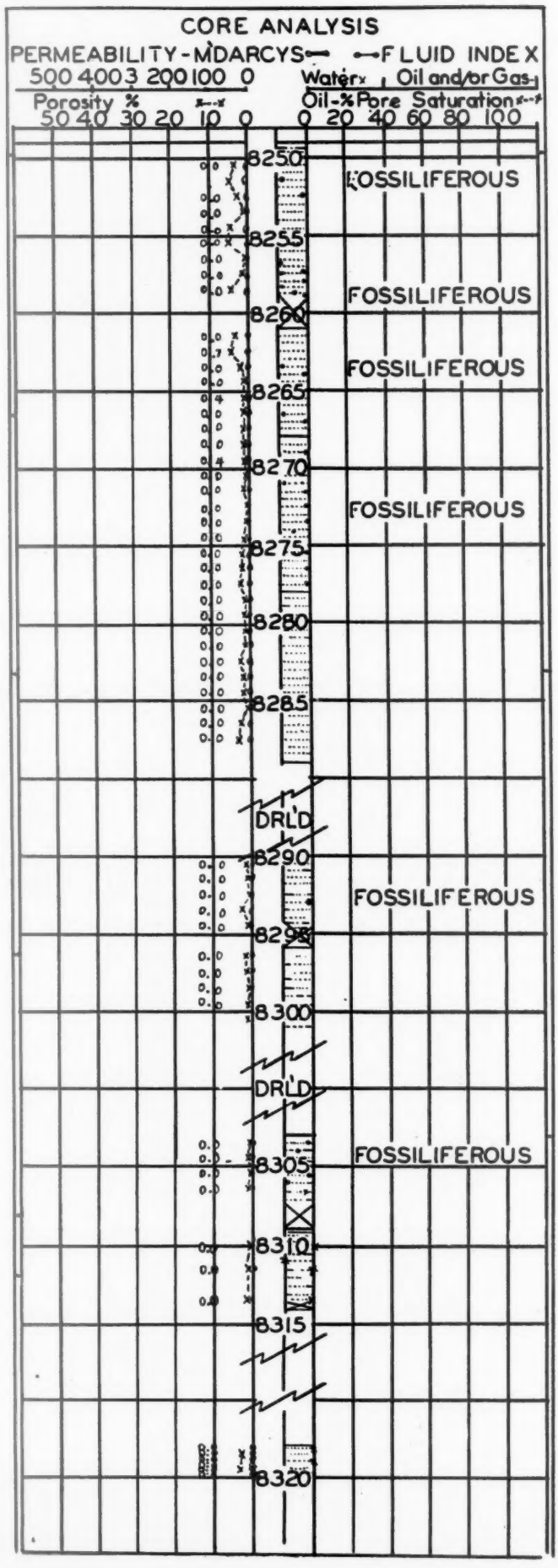
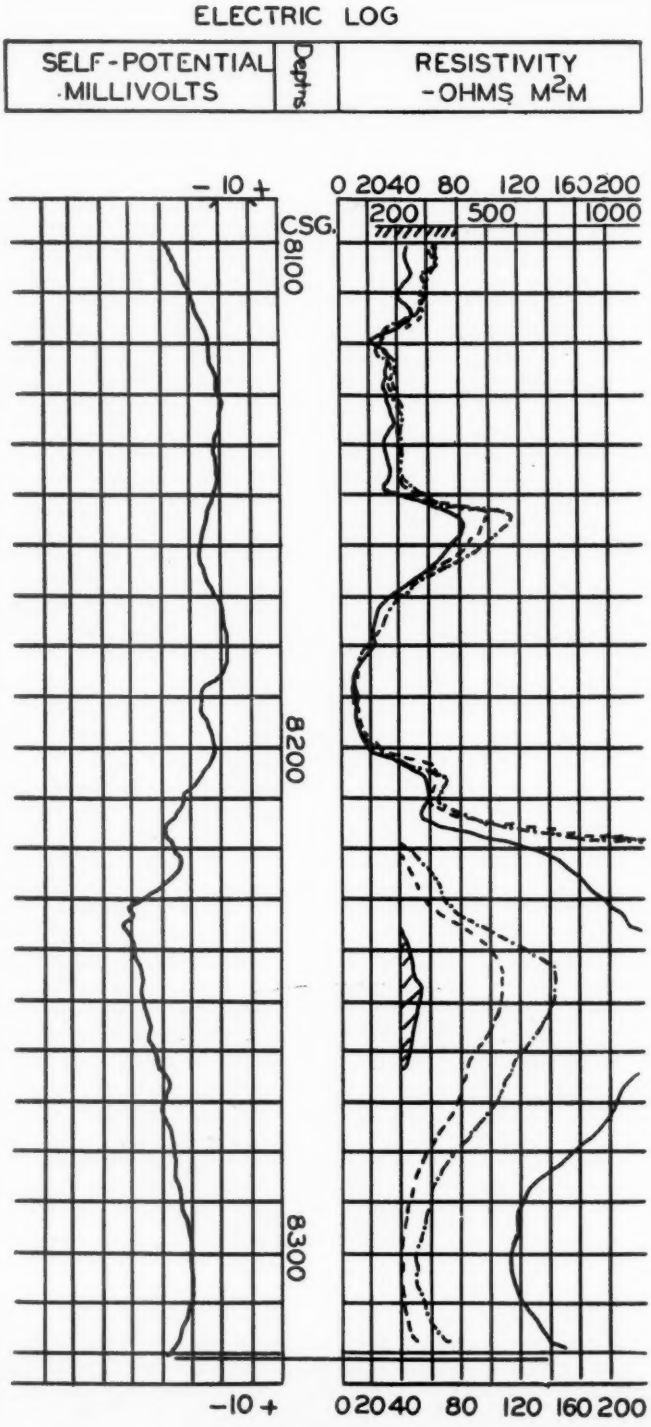
FIG. 3



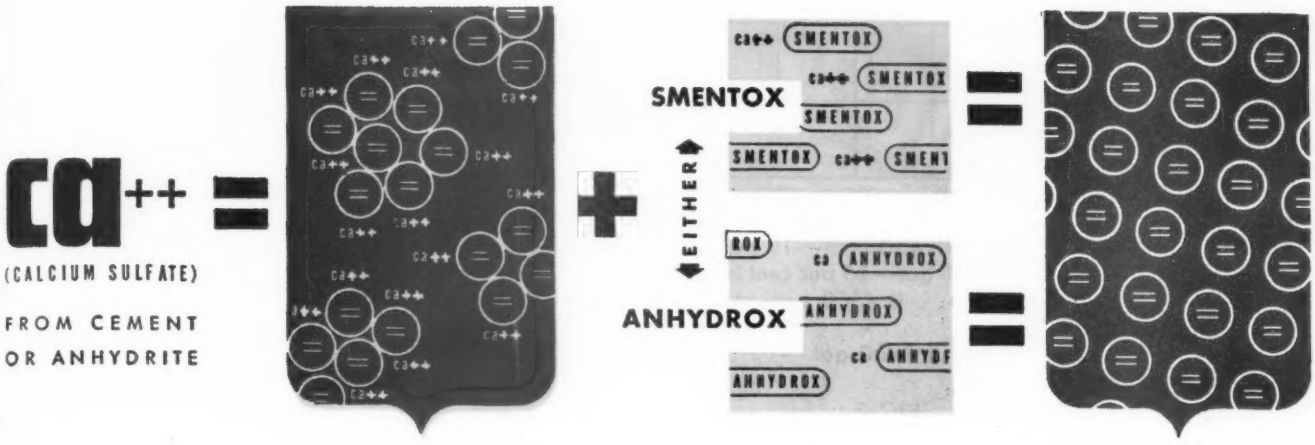
altitudes are required to lift mud from earthen mud pits.

The vibrating type mud screen when equipped with the proper mesh screen (20 to 30 mesh) has been very satisfactory for removing shale and cuttings from the mud. The vibrating screen is preferred to types that require water to be run continuously on the screen. Much of this water enters the mud, increasing treatments necessary to maintain the mud in a predetermined condition. When conditions permit, much mud may be saved by utilizing water to drill all cement plugs. If the use of water for such purpose is impossible or impracticable the mud should be conditioned for

FIG. 4



Calcium Flocculation* *Means Trouble!*



FLOCCULATION: *The grouping of the colloidal particles due to a reduction of their electrical charges*

Calcium sulfate drilling-mud contamination may occur in the formation, in underground waters, in surface waters, or from cement-cutting. The complete contamination (flocculation) may result in an air- or gas-cut mud, caving shale conditions, a water-block of the section, or stuck tools.

thickens drilling mud.
increases viscosity.
increases gel strength.
increases water loss.

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ANHYDROX: Complete ANHYDROX treatment of contaminated muds maintains or improves the good working characteristics of the mud before being contaminated. It lowers viscosity, lowers initial gel strength, and reduces water loss to normal for a non-contaminated mud.

SMENTOX: SMENTOX reconditions a cement-cut mud or prevents a mud from becoming cement-cut. Wall-building characteristics are often improved as SMENTOX contains colloids having this property. Frequently a SMENTOX-treated mud displays better performance properties than it did originally.

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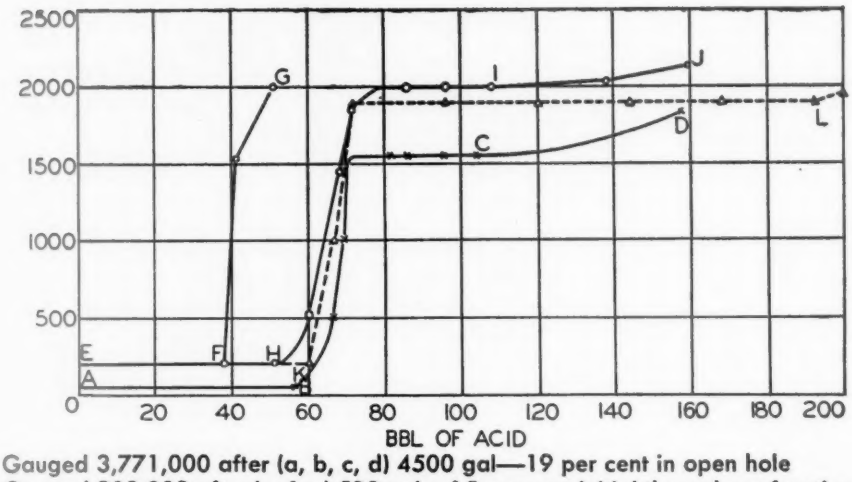

Gauged 3,771,000 after (a, b, c, d) 4500 gal—19 per cent in open hole
Gauged 900,000 after (e, f, g) 500 gal—15 per cent initial through perforations
Gauged 1,300,000 after (e, f, h, i, j) 4500 gal—15 per cent second stage through perforations
Gauged 4,150,000 after (e, f, k, l) 8700 gal.—10 per cent both zones after killing with mud

FIG. 5

cement contamination prior to the actual drilling of the cement. Such treatments prior to drilling cement requires less treatment and maintains the mud in much better condition while the cement is being drilled.

Mud and power-operated blowout preventers give assurance of complete control of high pressure zones and eliminate the dangers of blowouts and the hazards to property and life by fire.

The cost of mud and chemicals for mud treatment should not exceed $5000 for an 8000-ft well.

● **Completion.** *Casing and cementing.* Well completions with rotary tools offer several distinct advantages as compared with cable tools. Eight, nine, ten thousand feet or more of large diameter casing may be run and cemented with ease and safety in a 16 to 24-hr period utilizing rotary and floating equipment. The usual practice is to run a float shoe on the bottom of the casing and a float collar some 30 or 40 ft above the float shoe. The two floats give assurance that there will be no backflow of mud or cement into the casing and provide an accurate benchmark for positioning the last cement plug. Should conditions warrant, multiple-stage cementing jobs may be performed at the time the bottom of the pipe is cemented. Multiple-stage cementing jobs enable the operator to leave any desired section behind the casing free of cement.

High bottom hole temperatures are not found in this area and high temperature decomposition of mud or the necessity of retarded set cement is not a factor to be considered. Some retarded set cement, however, has been used to provide an additional safety factor on multiple-stage cementing jobs.

The service of rotary tools for deep Appalachian drilling eliminates the necessity of running successive strings of casing to shut off formation waters. The elimination of these casing strings reduces the expenditure for casing and enables the operator to drill a much smaller hole from the surface and at the same time reach the objective formation with a hole of sufficient size that any type of completion may be performed.

Cores and core analysis. Pay sections in the Appalachian area may be several hundred feet thick and have varying porosity and permeability. To evaluate properly any producing formation the permeability and porosity of the formation is highly important. Permeability and porosity tests may readily be conducted on cores taken with a conventional rotary core barrel. Fig. 3 shows the result of such permeability and porosity test as conducted on rotary cores from the Oriskany sand. Referring to Fig. 3, it will be noted the right-hand column provides for recording the fluid index, oil, gas, or water. The test for water only was conducted on the above cores. This test showed a negligible invasion of water from the drilling mud. Core recovery as a whole may be considered very good in this area. The percentage of recovery of the footage cored is approximately 84 per cent. All coring is done with conventional core barrel, as the formations are hard and cutter wear severe so no advantage would be gathered or time saved from the service of wire line core equipment. The average length core cut per cutter head is 8 ft. Cores may be obtained in any section of the hole that has a rate of penetration with a 10⅝-in. bit of more than 1 ft in 2 hr.

Electric log. Coring is expensive and a time consuming operation and it is desirable to eliminate all unnecessary coring in a field at the earliest possible date. The practice of coring key wells only and relying on electric logs for much of the correlation and evaluation work has been used extensively in other areas. Within localized areas a direct comparison between cores and electric logs on key wells, together with permeability and porosity determination on the cores and production figures will produce a set of values that may be used very satisfactorily for reservoir study on wells that are not cored but upon which an electric log has been run. Fig. 4 shows an electric log through the section corresponding to that shown on the core analysis, Fig. 3. In arriving at any set of values for use with electric logs in reservoir study all variables such as mud, hole size, and electrode spacing must be held constant for all wells within the area.

Selective acidization. Data on the ability of different parts of a thick producing section to produce are necessary if the maximum production is to be obtained from the well and intelligent forecast of future performance of the well is to be made. An example that illustrates the ease with which any number of similar intervals may be tested utilizing rotary tools and the difficulty of obtaining such information by other methods is shown in Fig. 5. The curves shown in Fig. 5 represent the pressures necessary to pump acid into various sections of the Oriskany sand. The curve ABCD represents the pressure required to pump 4500 gal of 15 per cent acid into the lower section of the Oriskany sand. Curves EFG and EFHIJ represent the pressure required to pump acid into the upper sections of the Oriskany sand. Each of the sections referred to were tested, acidized, and again tested exclusive of other productive zones in the hole. The increased pressure necessary to pump acid into the upper sections of the Oriskany as compared with the pressure required to pump acid into the lower section would make it impossible to acidize effectively the entire producing zone should these zones be exposed to acid simultaneously in the open hole. The curve EFKLM represents the pressure necessary to reacidize the Oriskany sand with 8700 gal of 10 per cent acid after killing the well with rotary mud and perforating and testing a section of the Devonian shale. The mud utilized to kill the well prior to the test conducted on the Devonian shale had a water loss of slightly greater than 12 cc for a full 30-min test. This high water loss, coupled with the difficulty of building a filter cake on the walls of the hole after it has been subjected to acid, substantiates the necessity of maintaining a low water loss mud. In instances where it is found necessary to kill a well after acidization the services of oil base mud or salt water may be preferable to conventional mud. Fresh water in some instances does not produce sufficient hydrostatic head to completely kill the well.

● **Summary.** The technique and performance of rotary for drilling the deeper horizons of the Appalachian area will continue to improve as each additional well is drilled and information obtained from past drilling in the area is utilized.

● **Acknowledgments.** The author is indebted to The Ohio Oil Company for permission to use data on rotary drilling from their files. The help and suggestions of F. E. Smith, general superintendent of production of The Ohio Oil Company and others is acknowledged.

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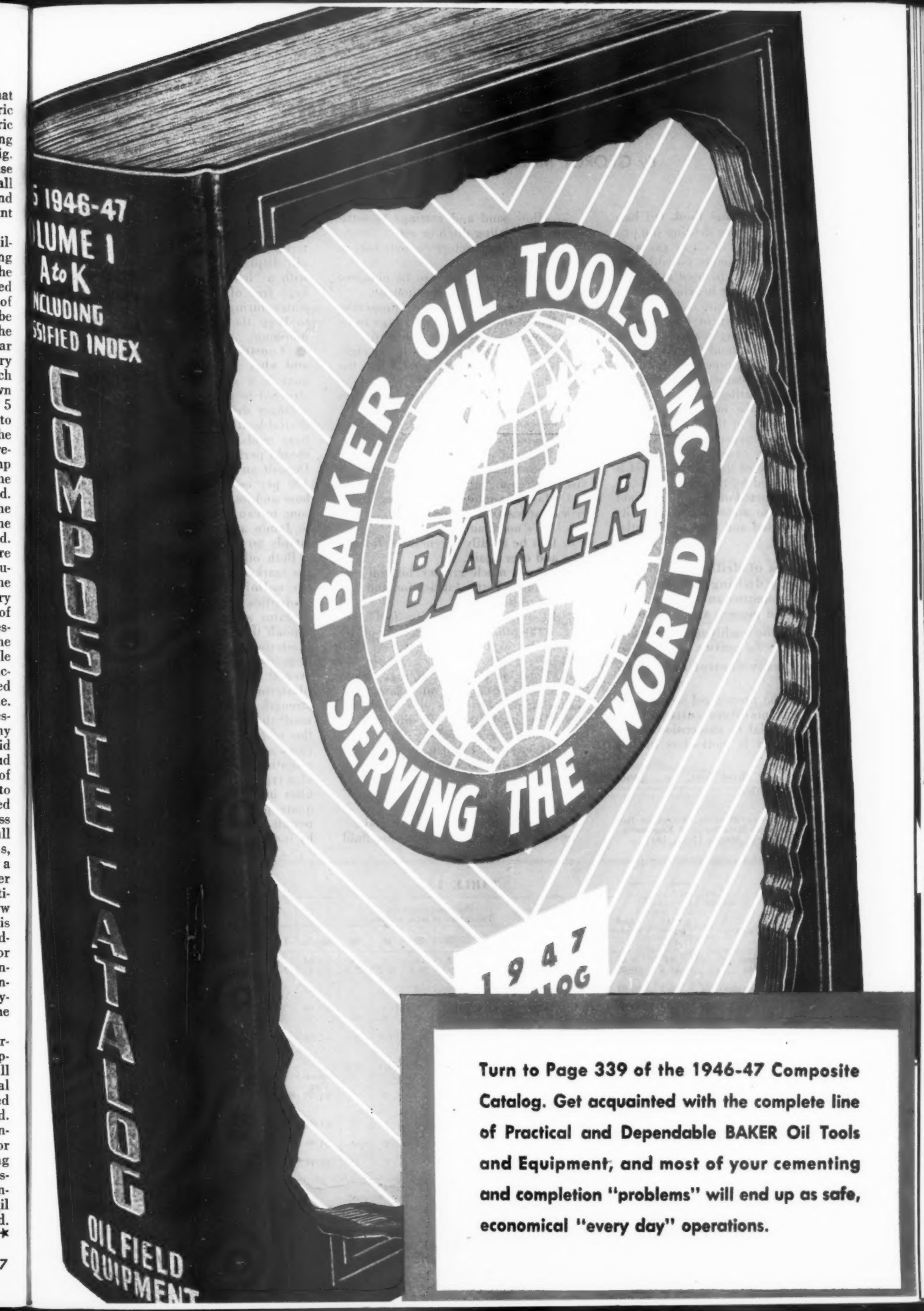
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Oil base drilling fluids*

By GEORGE MILLER, *President*, Oil Base, Inc.

● **Purpose of oil base mud.** Oil base mud is used mainly for drilling the producing zone or zones of oil or gas wells in order to give maximum possible productivity. It may also be used as a drilling medium to combat heaving shale or for drilling through salt domes, anhydrite, cement, gypsum, or other water-base mud flocculating materials. The main reasons shales tend to heave, other than due to lack of proper weight of the drilling fluid, is because they are either hydrous disintegrating, or are washed loose by excessive infiltration of the liquid components of the mud. Salt, anhydrite, cement, gypsum, etc., tend to flocculate a water base mud because the water or the base of this drilling fluid is adversely affected by these materials. A properly constructed oil base mud is not harmed by these materials because its base is unaffected and thus no flocculation occurs.

● **Properties of drilling mud.** The functions of a drilling fluid are well known. The properties an ordinary drilling fluid should possess are as follows:

1. Ability to be readily usable at most any desired specific gravity.
2. Allow ready control of the viscosity.
3. Possess the proper gel strength or thixotrophy to maintain cuttings and weighting material in suspension while the drilling fluid is motionless in the hole.
4. Have a low fluid loss, i.e., good plastering properties.
5. Allow sand and cuttings to settle out in the settling ditch or pit.
6. Permit satisfactory cement jobs to be obtained.
7. Allow good results to be obtained with electrical logging equipment.
8. Possess all of the above properties throughout the temperature range to be encountered in any particular well.

In addition to the above listed eight points a reliable oil base mud has the following features:

1. Has perfect plastering properties under normal API testing procedure, i.e., a zero fluid loss.
2. Is unaffected by salt, cement, anhydrite, gypsum, etc.
3. Does not gas-cut if used with proper viscosity range.
4. Has maximum deplastering properties (at least 96 per cent).
5. Does not foam or ferment.
6. Can be readily regenerated for use over and over again.
7. Allows much greater bit time on bottom due to better lubrication and less heat generation.
8. Eliminates the necessity for swabbing, scratching, or washing.
9. Forms a very thin mud cake (± 1/64-in.).
10. Contains no harmful ingredients to block the producing zone should the plastering properties be allowed to decrease by inadvertent oil dilutions or lack of adequate control.
11. Is easy to handle and requires minimum of additive materials for control.
12. Allows drilling of a "to gauge" hole.[1]
13. Permits accurate core analysis.

In order for an oil base drilling fluid to possess the above-named properties it must be made from certain correct materials, mixed with the proper type of oil, displaced after use from the well with a "live" crude oil, and should be kept free of any excessive amounts of water during its use or storage in order to keep the cost of regeneration to a minimum.

● **Construction of a good oil base mud and why.** A well-formulated oil base mud is a synthetic drilling fluid constructed to perform all functions of an ordinary drilling mud and offer certain desirable attributes not present in water base muds. A desirable oil base mud should perform the following functions: Deposit an ultra-thin mud cake, permit 100 per cent deplastering of the well bore and lose no water to the producing zone to cause decreased production due to Jamin action[2,3] or by what is more simply termed "water blocking."[13]

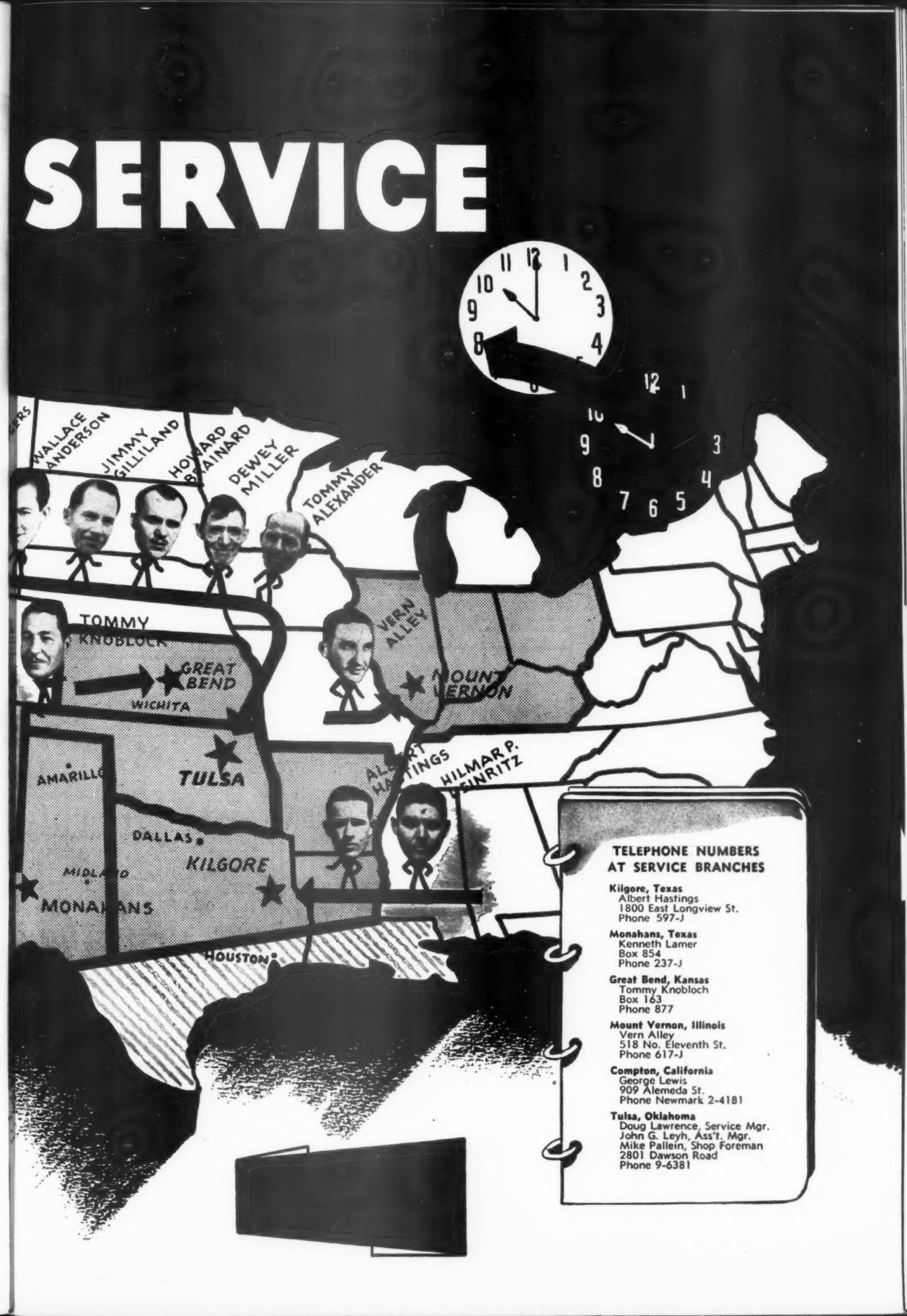
Both oil base drilling fluids now on the market rely on air blown asphalt as the colloidal medium for plastering properties. One of these oil base fluids contains a special type of air blown asphalt that will not only give excellent plastering properties but also provide a large part of the necessary gel strength even at high temperatures.[4] Where good plastering characteristics and proper gel strength are not inherent in the asphalt used[5] they may be provided by the addition of gelling ingredients[6] and in some cases additional colloidal material.[7] It is essential that any additives shall not be of a type to cause blocking should they filter into the producing zone.[8] Inadequate plastering properties that would permit this infiltration might be caused by inadvertent oil dilutions, wrong type

*Presented at Annual Meeting, American Institute of Mining and Metallurgical Engineers, New York, New York, March 17-22, 1947.

TABLE 1

Type oil	Location	API gravity, deg.	Acid number	Aniline point, °F	Plastering properties Throughput in ml in minutes 0	5	10	15	30	45	60	Cake, in.	Gel strength T.S.	B.S.	Gel	Remarks
Diesel	California	34	0.51	140	0	0	0	0	0	0	0	±1/64	No	No	V.G.	Very good mixing oil.
Gas oil	Columbia	38.6	<0.05	176	0	10.3	13.9	17.6	26.4	32.7	37.9	±1/4	No	Small	No	A very bad mixing oil.
Gas oil plus high aromatic gas oil	Columbia plus Calif.	36.2	<0.05	138	0	0	0	0	0	0	0	±1/64	No	No	Good	Mixing oil almost repaired.
Above blend plus 0.2% Chem "V"	Columbia plus Calif.	36.2	0.56	138	0	0	0	0	0	0	0	±1/64	No	No	V.G.	Now a good mixing oil.
Gas oil	Wyoming	22.4	0.18	148.5	0	0	0	0	0	0	00	±1/64	No	No	V.V.V.G.	Mud much too thick. Mixing oil too low gravity.
Distillate	Colorado	44.6	0.01	154	0	0	0	0	0.1	0.5	0.7	±1/32	Slight	No	Fair	Mixing oil too high gravity, fairly high aniline pt., acid number too low.
Benzol	Pennsylvania	29.6	<0.05	zero	0	0	0	0	0	0.1	0.3	? Bad settling	Bad	Bad	No	Aniline pt. much too low. Bad settling gave erroneous plastering test.
Gas oil (cracked)	Oklahoma	31.5	<0.05	86	0	0	0	0	0	0	0	±1/64	Slight	No	Weak	Acid number too low. Add Chem "V".
Gas oil plus 0.2% Chem "V"	Oklahoma	31.5	0.50	86	0	0	0	0	0	0	0	±1/64	No	No	Good	Much improved, raising aniline pt. will also help.
Gas oil	California	32.5	1.60	133	0	0	0	0	0	0	0	±1/64	No	No	V.V.G.	Acid number too high. Gel strength too high.
Gas oil	California	32.5	0.50	133	0	0	0	0	0	0	0	±1/64	No	No	V.G.	Very good mixing oil.

Standard test samples used for all tests.
T.S. = Top settling.
B.S. = Bottom settling.
V.G. = Very good.
V.V.G. = Very very good.
Plastering properties tested with 100 psi wall building tester.


SERVICE
WALLACE ANDERSON
JIMMY GILLILAND
HOWARD BRAINARD
DEWEY MILLER
TOMMY ALEXANDER
TOMMY KNOBLOCK
GREAT BEND
WICHITA
VERN ALLEY
MOUNT VERNON
AMARILLO
TULSA
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Tommy Knobloch
Box 163
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George Lewis
909 Alemeda St.
Phone Newmark 2-4181
Tulsa, Oklahoma
Doug Lawrence, Service Mgr.
John G. Leyh, Ass't. Mgr.
Mike Pallein, Shop Foreman
2801 Dawson Road
Phone 9-6381

of mixing oil, or material dilutions that largely change the ratio of correct proportions of the colloidal material present.

In regard to deplastering properties and mud cake removal there are a few points that will bear noting.

Ordinarily when a well has been completed with water base mud, this mud is removed as much as possible from the well by displacing it with water or oil or by swabbing or bailing.

A clay-water mud cake is only diluted and not disintegrated when washed with water or crude oil. The same general point applies to oil base muds. If an oil base mud was constructed to stay together with crude oil as the base, its mud cake will only be diluted when the mud displacement takes places with crude oil. Oil base muds must be made with a refined type of oil as the fluid phase in order that the wall cake laid down can actually be chemically disintegrated while being displaced with live crude oil.

All oil base muds are adversely affected by water, some to greater extents than others. The two main effects, depending upon the degree of water contamination, are increased viscosities and settling of the weighting material, which becomes water wet. Thus the holding of water contamination of oil base drilling fluids to a minimum is very important. One oil base drilling fluid can be cheaply and successfully regenerated from water contamination. This is accomplished by the use of a special type of unslacked lime in accordance with U. S. Patent 2,316,967. If any so-called regenerating material is water soluble then obviously it does not remove the water and thus regeneration has not been obtained.

Water content of oil base muds containing asphalt are only obtainable by means of an ASTM distillation test—they cannot be determined by centrifuging, emulsion breaking chemicals, or by a filter press.

Cementing can be done with excellent results in certain formulated oil base muds; however, less than 16-sack jobs have been more or less hit or miss as in water base muds. Due to the thin wall cake, a good bond is made, facilitating the cementing job. No water should be run ahead of or behind the cement. No appreciable results have been effected by this practice and it only adds to the contamination of the oil base mud. Plastic cement has recently been used with much success in oil base mud. This type of cement has no water loss and thus is excellent for oil or gas zone work. As low as a 26-gal job has been completed successfully.

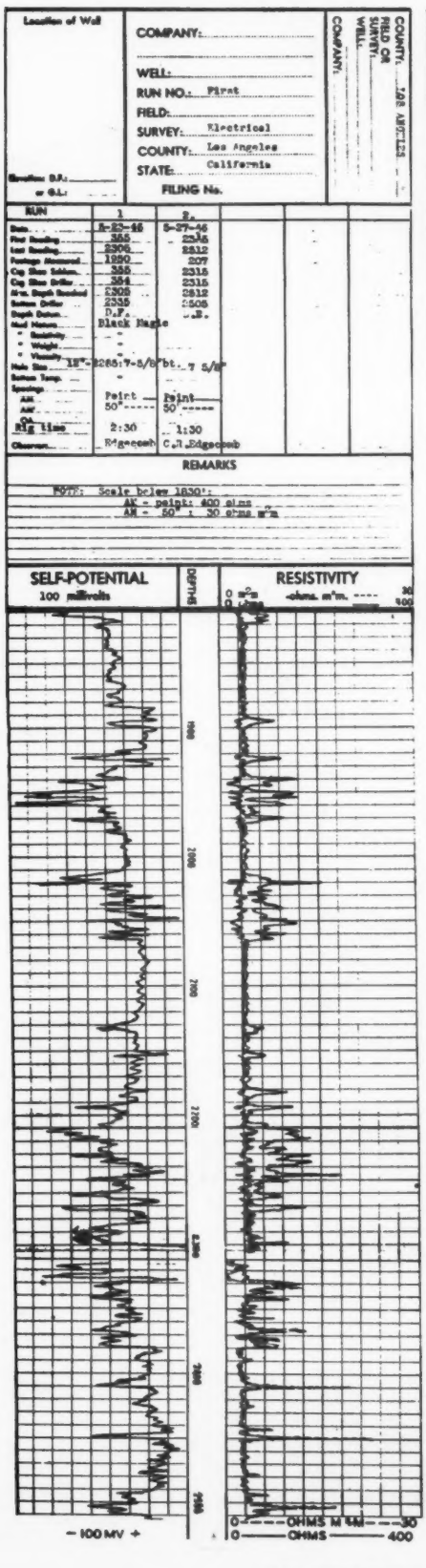
For accurate core analysis, the drilling fluid used must lose a minimum

TABLE 2—Fig. 1
STATE—California

	Offsetting wells	
	Oil base	Water base
Initial production:		
Bbl per day	369	330
Cut, per cent	0.2	0.1
Flow bean, in.	12/64	11/64
Later production:		
Months later	3	10
Bbl per day	350	284
Cut, per cent	0.1	0.2
Flow bean, in.	12/64	10/64
Bottom hole pressure, psi	2250	2370
Producing zone interval, ft	178	170
Type of producing zone	Sand	Sand
Approx. permeability, md	600	600 (est)
P. I.	250.	60.
Remarks:		
P.I. at initial rate	Flowing in tanks 45 min after bringing in (clean-up time)	Flowing in tanks 4 hr after bringing in (clean-up time)

FIG. A

No. 1



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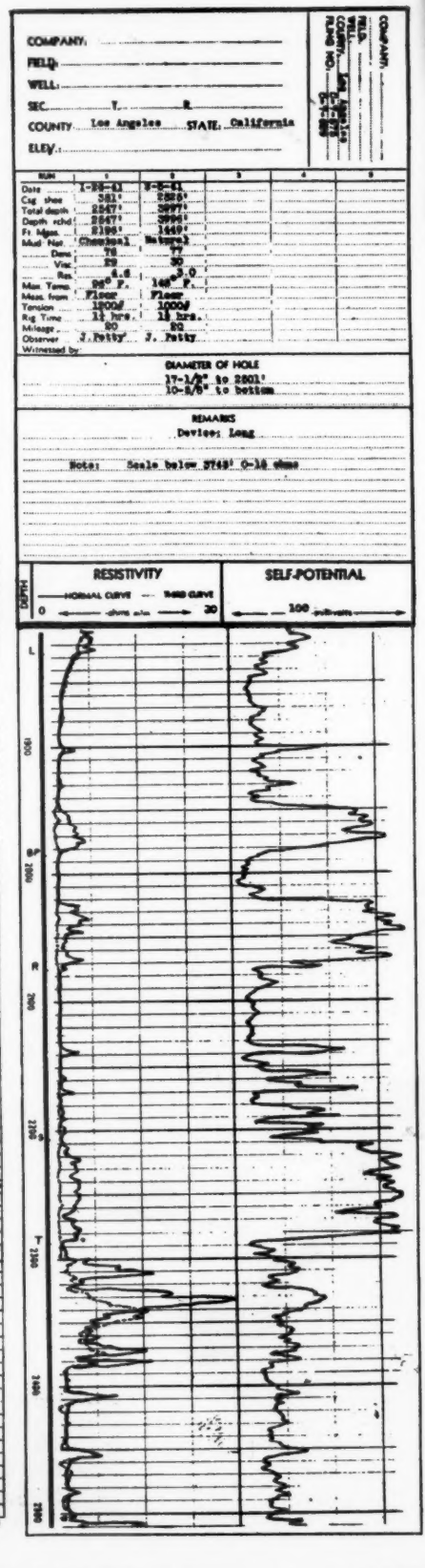


Oilfield

Here, for the first time, is a comprehensive attempt to show actual *usable* horsepower ratings for various oil field services. By referring to the following tables, any operator can tell at a glance just what power he *will get* from any BUDA Oilfield Engine Model... data never before offered by an engine manufacturer.

BUDA NATURAL GAS OIL FIELD ENGINE SERVICE RATINGS

Model	Maximum HP @ RPM	65% Production Pumping HP @ RPM	70% Pipe Line Pumping HP @ RPM	75% Mud Pumps HP @ RPM	80% Drilling Hoisting HP @ RPM	85% Well Servicing HP @ RPM
4-B-153	49 @ 2800	22 @ 1600	24 @ 1600	28 @ 1800	33 @ 2000	39 @ 2400
6-B-230	73.5 @ 3200	31 @ 1600	34 @ 1600	40 @ 1800	46 @ 2000	56 @ 2400
HP-326	79.5 @ 2600	37 @ 1400	40 @ 1400	48 @ 1600	55 @ 1800	62 @ 2000
K-428	108 @ 2400	48 @ 1400	52 @ 1400	62 @ 1600	72 @ 1800	83 @ 2000
L-525	113 @ 2400	57 @ 1400	61 @ 1400	72 @ 1600	83 @ 1800	93 @ 2000
LO-525	157 @ 2400	67 @ 1400	72 @ 1400	87 @ 1600	101 @ 1800	114 @ 2000
JL-1335	194.5 @ 1350	109 @ 1000	117 @ 1000	134 @ 1100	150 @ 1200	164 @ 1300
MO-893	188 @ 1800	100 @ 1200	107 @ 1200	128 @ 1400	141 @ 1500	150 @ 1800
PC-1879	242 @ 1200	142 @ 900	153 @ 900	175 @ 1000	192 @ 1100	206 @ 1200
6-PCG-1879†	340 @ 1200	172 @ 900	185 @ 900	220 @ 1000	256 @ 1100	289 @ 1200
PCS-1879*						

*Supercharged †Convertible

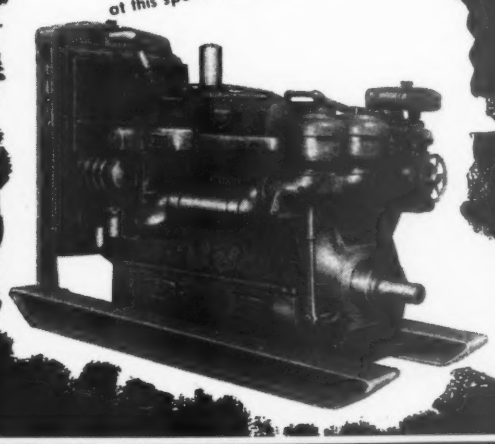
NOTE: Engine speeds shown for various types service are MAXIMUM recommended. Many operators prefer lower speeds for longer engine life. In these cases select desired engine operating speed and refer to Maximum HP shown on Buda oil field power curve and take percentage (%) of Maximum HP shown above for each type service. Ex: assume it is desired to operate Model HP-326 in "pipeline service" at 1200 RPM Power curve shows 50 BHP at this speed. Taking 70% of 50 BHP = 35 usable HP @ 1200 RPM.

BUDA DIESEL OIL FIELD ENGINE SERVICE RATINGS

Model	Maximum HP @ RPM	65% Production Pumping HP @ RPM	70% Pipe Line Pumping HP @ RPM	75% Mud Pumps HP @ RPM	80% Drilling Hoisting HP @ RPM	85% Well Servicing HP @ RPM
4-BD-153	40 @ 2400	20 @ 1600	22 @ 1600	26 @ 1800	29 @ 2000	33 @ 2200
6-BD-230	60 @ 2400	31 @ 1600	33 @ 1600	38 @ 1800	44 @ 2000	49 @ 2200
6-DT-317	90 @ 2300	44 @ 1600	48 @ 1600	57 @ 1800	65 @ 2000	77 @ 2200
6-DT-468	113 @ 2000	59 @ 1400	63 @ 1400	72 @ 1500	80 @ 1600	92 @ 1800
4-DC-645	119 @ 1400	62 @ 1100	67 @ 1100	78 @ 1200	83 @ 1200	101 @ 1400
6-DC-844	180 @ 1800	89 @ 1200	96 @ 1200	117 @ 1200	131 @ 1500	153 @ 1800
6-DCS-844*	225 @ 1800	109 @ 1200	117 @ 1200	128 @ 1200	164 @ 1500	192 @ 1800
8-DC-1125	240 @ 1800	119 @ 1200	128 @ 1200	145 @ 1400	176 @ 1500	204 @ 1800
8-DCS-1125*	300 @ 1800	145 @ 1200	156 @ 1200	157 @ 1400	218 @ 1500	255 @ 1800
6-DC-1879	258 @ 1200	140 @ 900	150 @ 900	194 @ 1400	198 @ 1100	218 @ 1200
6-PCD-1879†	330 @ 1200	174 @ 900	187 @ 900	174 @ 1000	251 @ 1100	281 @ 1200
6-DCS-1879*				218 @ 1000		

*Supercharged †Convertible

NOTE: Engine speeds shown for various types service are MAXIMUM recommended. Many operators prefer lower speeds for longer life. In these cases select desired engine operating speed and refer to Maximum HP shown on Buda oil field power curve and take percentage (%) of Maximum HP shown above for each type service. Ex: assume it is desired to pull "Mud pump" with Model 6-DC-844 operating at 1200 RPM Power curve shows 137 BHP at this speed. Taking 75% of 137 BHP = 102 usable HP @ 1200 RPM.



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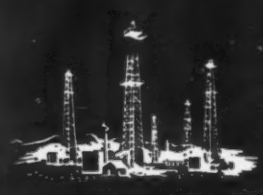


amount of fluid to the formation so that the core taken will be unflushed and the center portion of it will be uncontaminated. Water base muds do not possess this desirable feature.[9]

Oil base mud, since it contains oil, is injurious to ordinary rubber and some inferior grades of synthetic rubber. However, this problem has recently been solved and adequate synthetic rubber products such as pump valves, pistons, pipe protectors, pipe wipers, etc., are now on the market.

In general it has been found that in hard shale or very hard sand the drilling rate with oil base mud is somewhat slower than with water base mud (unless a diamond bit is used)[10] due to the fact that it does not filter water ahead of it to soften the formation.

Due to the fact that there is no solution of the formation drilled, minimum pump pressures should be maintained. Reduced pump pressures have the effect of lengthening the useful life of rubber parts of the drilling equipment that comes in contact with oil base mud.

In ordinary sand or sandy shale the drilling rate is faster than with water base mud because instead of washing loose the formation, a "to gauge" hole is drilled and longer "time on bottom" may be maintained due to better lubrication and less heat generation. On the average, the drilling rate with oil base or water base mud is comparable.

Ordinarily oil base mud is used mainly to drill into the oil zone and this is done after casing has been set above the zone. By this means less oil base mud is needed for circulation and initial cost outlay is reduced. If casing has been set, obviously a smaller hole than the one in which the casing is set must be drilled into the zone. If it is desired to drill the same size hole all the way to bottom in order to eliminate the hanging or cementing of a liner, and thus run casing and gun perforate, the following suggestion is offered in order to keep from losing a substantial amount of oil base mud behind the casing after the drilling is finished and the casing is cemented in

TABLE 2—Fig. 2
STATE—California

	Offsetting wells	
	Oil base	Water base
Initial production:		
Bbl per day	1563	558
Cut, per cent	0.4	1.0
Flow bean, in.	48/64	1
Later production:		
Months later	11	14
Bbl per day	311	125
Cut	0.8	2.0
Flow bean, in.	10/64	10/64
Bottom hole pressure, psi	3635	3580
Producing zone interval, ft	110	90
Type of producing zone	Oil sand	Oil sand
Approx. permeability, md	60	60
P. I.	1.42	0.144
Remarks:		
P.I.'s run 3 months after completion. After initial production both wells choked down.	Completed 12/28/45. Tubing pressure for above "Later production," 1450 psi.	Completed 8/14/45. Tubing pressure for above "Later production," 700 psi.

TABLE 2—Fig. 3
STATE—California

	Offsetting wells	
	Oil base	Water base
Initial production:		
Bbl per day	1575	1030
Cut, per cent	0.1	0.1
Tubing pressure, psi	530	520
Casing pressure, psi	1300	840
Flow bean, in.	40/64	64/64 and 14/64
Later production:		
Months later	4	4
Bbl per day	525	282
Cut, per cent	0.1	3.2
Tubing pressure, psi	300	300
Casing pressure, psi	700	500
Flow bean, in.	32/64	40/64
Bottom hole pressure, psi	1834	1450
Producing zone interval, ft.	270	260
Type of producing zone	Oil sand	Oil sand
Approx. permeability, md	300	300
P. I.	5.73	1.22
Remarks:		
Operator states that difference in bottom hole pressures is due to rapid depletion of zone in area.	Well completed 9/46	Well completed 9/46
Gravity of oil produced, °API	30.4	30.7

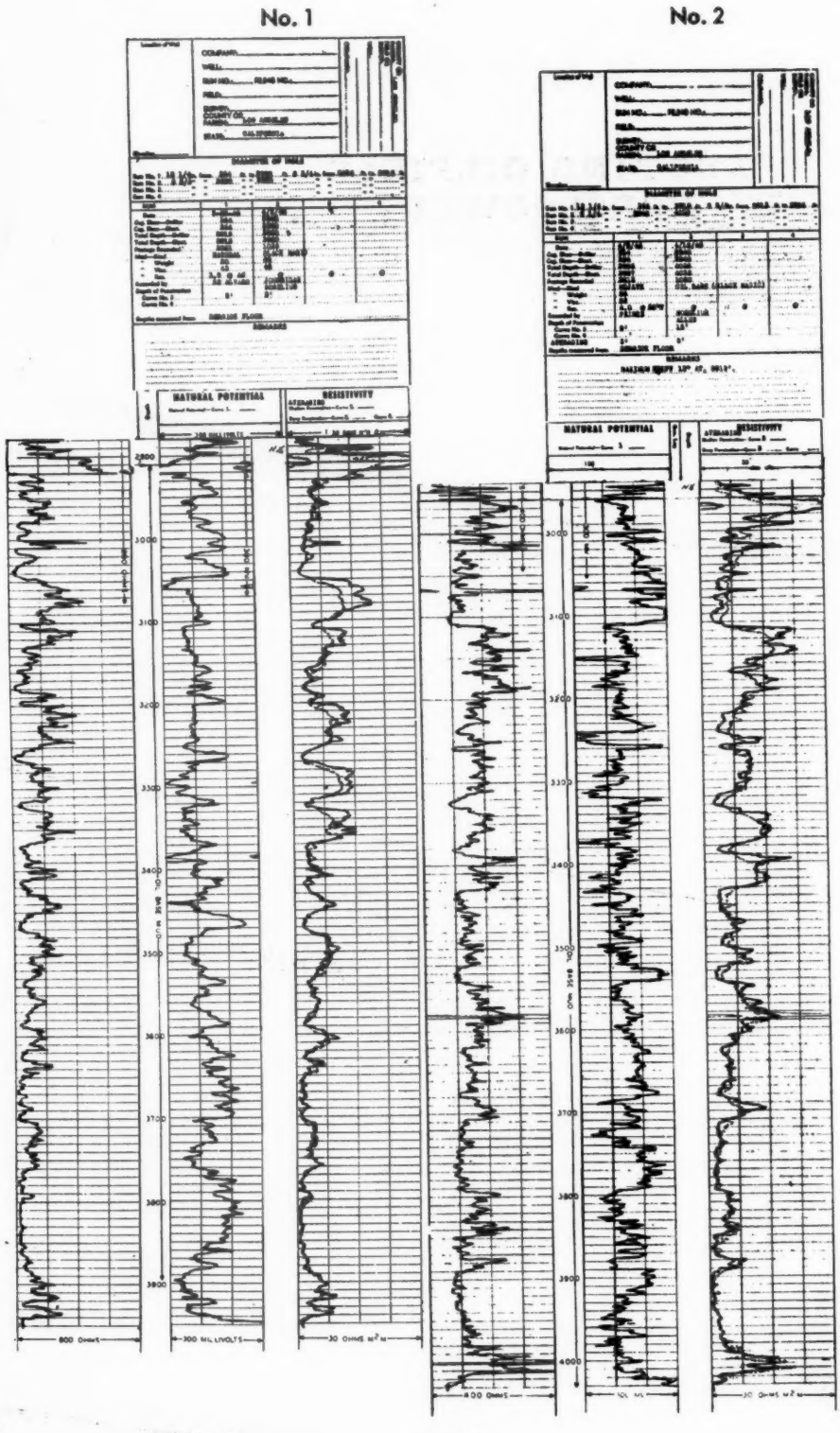
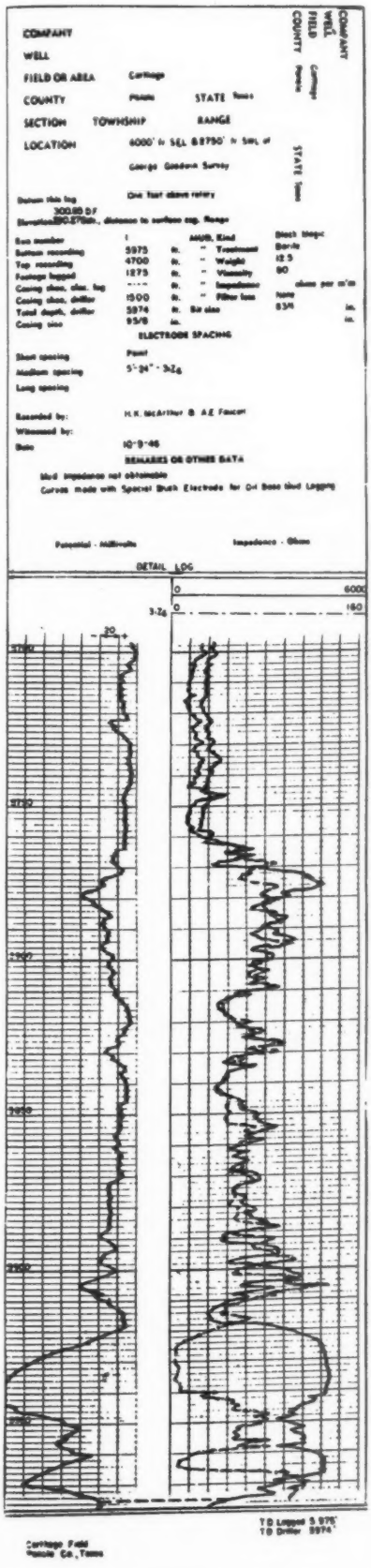


FIG. B

FIG. C

No. 1



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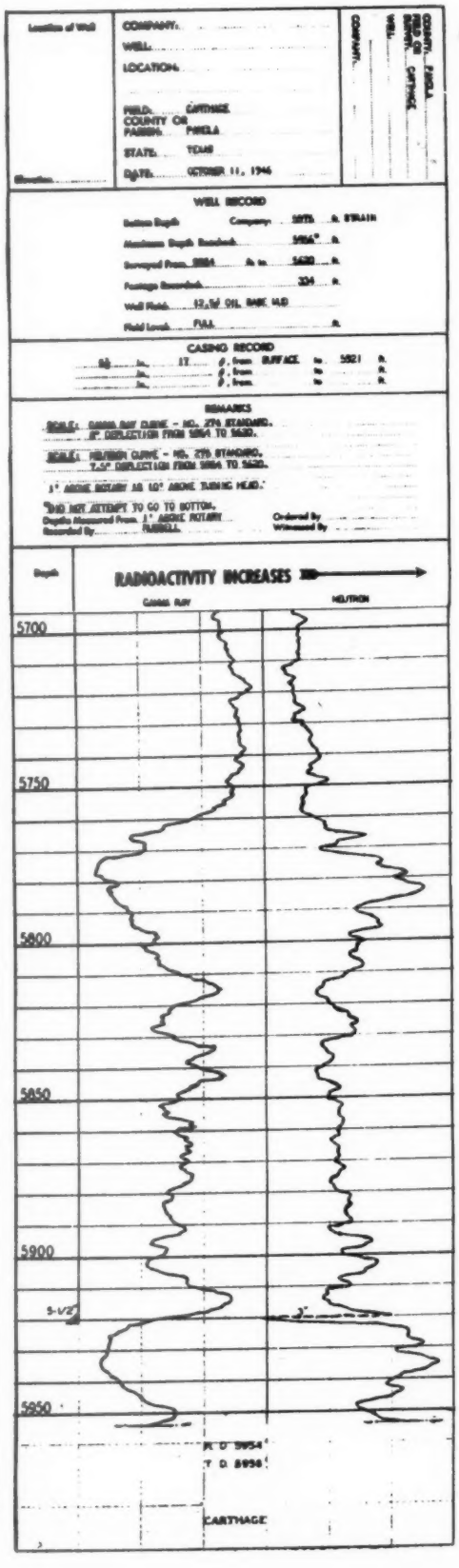

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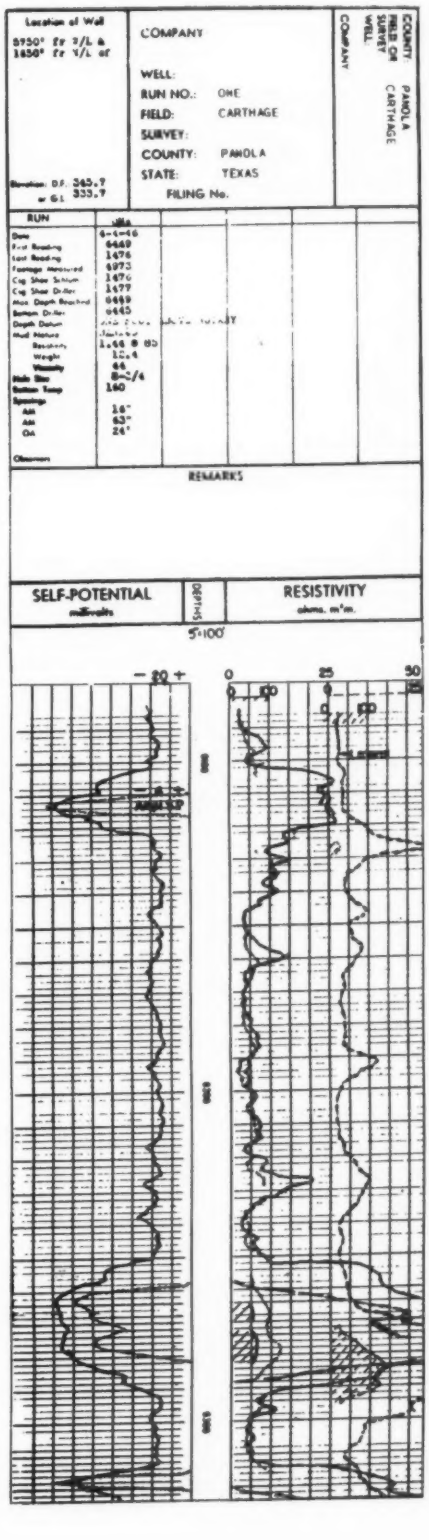

TABLE 2—Fig. 4

STATE—California

	Comparable wells			
	Oil base		Water base	
Well	A	B	C	D
Initial production:				
Bbl per day	730	509	325	284
Cut, per cent	0.1	0.1	0.3	0.4
Flow bean	P	P	P	P
			Pumps speeded up for purpose of taking P. I.	
Later production:				
Months later	No data—pumps slowed down under proration.		21	21
Bbl per day			400	524
Cut, per cent			0.8	2.6
Flow bean			P	P
Bottom hole pressure, psi	815	780	775	1005
Producing zone interval, ft	1180	1220	1060	1100
Type of producing zone	Oil sand	Oil sand	Oil sand	Oil sand
Approximate permeability, md	400	400	400	400
P. I.	6.46	6.69	2.35	4.58
Remarks:				
Gravity of oil produced °API	18.4-19.1	19.6-19.9	20.1-21.3	21.2-20.6
None of wells pumped down.	Well completed 2/46	Well completed 3/46	Well completed 7/44 Bottom hole press. at 4/46 703 psi	Well completed 7/44 Bottom hole press. at 4/46 814 psi

place: (a) Drill to the top of the oil zone with conventional mud; (b) change to oil base mud; (c) drill the oil zone; (d) pull the drill pipe up to the top of the oil zone and displace the oil base mud with the conventional mud; (e) run casing to bottom and cement it using oil base mud to force the cement down the casing; (f) gun perforate as desired; (g) run tubing and displace the oil base mud with "live" crude oil.

In this manner about the only oil base mud that will be lost is the amount left in the oil zone interval prior to running casing, which now of course will be ahead of the cement and behind the casing.

As it has been previously pointed out that a good oil base mud has all the necessary properties of a water base mud and many additional features, it thus follows that there is no reason why long intervals of open hole drilling cannot be accomplished the same as with a water base mud. To date oil base mud has been used in open hole in excess of 8000 ft in California and in more than 7000 ft in Louisiana with good results.

In regard to the cost of oil base mud, it is initially more expensive than water base mud because it is made with oil instead of water; however, since a good oil base drilling fluid can be used over and over again, the actual cost of it is only the amount used and lost on each well, which with adequate control and supervision amounts to an average of about 10 per cent. When the final cost is thus examined, it has been found in a great many cases that this cost is actually comparable with the use of water base mud. Quite frequently if the savings effected by the use of fewer bits and reamers, fewer round trips, lack of swabbing time and production clean-up time, are converted into dollars and cents the relative cost of using oil base mud is negligible.

Special equipment other than oil resistant rubber products is not necessary, although as with any mud, substantial time and money can be saved if the drilling rig is equipped adequately with the proper tankage, mud guns, portable suction pits, and ditches. If sacked oil base material is used, a heating coil in the mixing pit will facilitate the mixing. If premixed oil base mud is used, no heating coil is necessary.

There are two features about an oil base mud that should be better understood. There is the possibility of fire with any oil solution. This is considerably less possible with a good oil base mud than if straight crude oil were being circulated, however, as the flash point of the average oil base mud is approximately 230 F. It is a matter of record that with one type of oil base drilling fluid that there has not been a rig fire in well over 1000 jobs. Also it has been noted that on many jobs, with this particular type of oil base mud, the crew smoked continuously around the rigs. Normal precautions should be taken in regard to fire even though the possibilities are remote.

Second, as all present commercial types of oil base mud contain asphalt, they vary in color from dark brown to black. This feature usually has adverse psychological effect upon a drilling crew doing their first oil base job. However, with adequate control and cooperation a rig can be kept as clean as desired and in some cases when the companies use covered pits and ditches and pipe wipers, the oil base mud is scarcely seen by the crew. Unlike crude oil, a good oil base mud will plaster and not penetrate work clothes as experienced by men in the rod gangs. If the oil base mud does not contain lampblack or other ingredients undesirable from the personnel standpoint it may be removed from skin or clothing with cleaning solvent, hand cleaner, grease removing soaps, etc.

● **Effect of different types of mixing oil on oil base drilling fluids.** The type of mixing oil used for any oil base mud containing blown asphalt as the plastering agent is very important as the results show in Table 1. Even though the correct materials and proper proportions are used to manufacture an oil base mud, if the wrong type of mixing oil is used for the base, the plastering properties, gel strength, viscosity, weight, deplastering properties, and even the initial ability to mix the proper materials together to form the mud, will suffer. These general facts may be listed as follows:

1. The weight of the drilling fluid will vary approximately 2 lb per cu ft directly with the API gravity of the mixing oil—in general, the lower the gravity, the higher the weight of the resulting mud.

2. The viscosity of the drilling fluid will vary with the gravity and acidity of the mixing oil—in general, the lower the gravity and the higher the acidity, the higher the viscosity.

3. The gel strength will vary with the acidity, aromatic content, gravity, boiling points, aniline point, and surface tension of the mixing oil.

4. The plastering properties will vary with the aniline point, acidity, gravity, aromatic content, surface tension, and

TABLE 2—Fig. 5

STATE—California

	Comparable wells					
	Oil base			Water base		
Well	A	B	C	D	E	F
Initial production:						
Bbl per day	117	97	128	72	87	52
Cut, per cent	17	10	2	24	23	58
Flow bean	P	P	P	P	P	P
Later production:						
Months later	1/3	1/3	1	1 | 6	1 | 3	2
Bbl per day	108	94	125	79 | 92	84 | 85	47
Cut, per cent	12	7	5	12 | 8	11 | 8	45
Flow bean	P	P	P	P	P	P
Bottom hole pressure, psi	220	220	173	220	220	220
Producing zone interval, ft	589	588	573	626	580	539
Type of producing zone	Oil sand	Oil sand	Oil sand	Oil sand	Oil sand	Oil sand
Approximate permeability, md	300	300	300	300	300	300
P. I.	1.35	0.66	0.86	0.40	0.38	0.135
Remarks:	Well never pumped down.	Well never pumped down.	Pumping at capacity	Pumping at capacity	Pumping at capacity	Pumping at capacity
	Poor pump efficiency	For last 30 days since above data, has been making 106 bbl per day net.				

AS NATURAL TOGETHER AS HAM AND EGGS

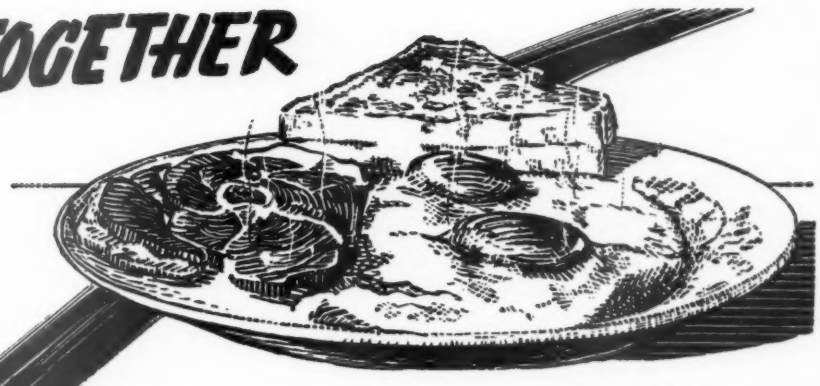

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TABLE 2—Fig. 6
STATE—California

	Offsetting wells	
	Oil base	Water base
Initial production:		
Bbl per day (net)	944	552
Cut	..	..
Flow bean (production test)	?	?
Later production:		
Months later	6	6½
Bbl per day (net)	251	133
Cut	..	..
Flow bean (production test)	?	?
Bottom hole pressure, psi	455	564
Producing zone interval, ft	26	24
Type of producing zone	Oil sand	Oil sand
Approx. permeability, md	1100-3000	1100-3000
P. I.	4 65	0.90
Remarks: Data taken from API Paper No. 901-22-F. See bibliography (9.)		

TABLE 2—Fig. 7
STATE—California

	Offsetting wells	
	Oil base	Water base
Initial production:		
Bbl per day (net)	374	88
Cut	..	..
Flow bean (production test)	?	?
Later production:		
Months later	3	1
Bbl per day (net)	423	65
Cut	..	..
Flow bean (production test)	?	?
Bottom hole pressure, psi	136	110
Producing zone interval, ft	35	31
Type of producing zone	Oil sand	Oil sand
Approx. permeability, md	1100-3000	1100-3000
P. I.	7.5	0 98
Remarks: Data taken from API Paper No. 901-22-F. See bibliography (9).		

lighter fraction content of the mixing oil.

Thus, from the above points it is seen that a set of general specifications for the mixing oil[11] should be formulated and these specifications in one case are as follows:

Gravity	29°- 40° API
Flash point	130- 180 F
Initial boiling point	320- 420 F
Final boiling point	500- 650 F
Acid number	0.20-1.50
Aniline point	90- 150 F
Surface tension	Less than 24 dynes per cm.

The two most important specifications of the above list are the aniline point and acid number. Both can be altered in the field quite simply so that obtaining the right type mixing oil is no longer a problem. If the aniline point is too high, it can be reduced by blending with the selected oil some aromatic or "cat cracker" type oil—this blending oil having an aniline point of preferably not below 90 F. If the aniline point of the selected oil is too low, it can be raised by blending with some "straight run" type oil or some paraffinic type oil. If the acid number is too low, this can be rapidly raised by the addition of a special petroleum fatty acid or napthenic acid now commercially available.[11]

● **Comparative analysis of electric logs.** Briefly, the main changes that have been made[12] in equipment in order to log in oil base are the use of contact or brush type electrodes, either an oil resistant or steel cable, and a new electrical hook-up. Fig. A shows the results of a test conducted by an oil company in the Wilmington field in California to prove whether or not known water sands could be successfully logged with oil base mud. These logs are for two different straight hole wells located about 150 ft apart. One was drilled and logged with water base mud in 1941 and the other was drilled and logged with oil base in May, 1946. In this particular well, the drilling mud was changed to oil base at approximately 1900 ft and the hole drilled through known water sands and then logged electrically. The correlation may be readily seen.

Fig. B represents the oil zones of two routine oil base completions. These logs were made by a different company than those of Fig. A. No nearby water base mud logs are presented for correlation, for the only water base mud wells offsetting these oil base wells have become wet since they were drilled some six years ago. The third curves and detail curves may be readily seen.

Fig. C represents the gas zones of two nearby lime producing zone wells in a Texas field. The water base log was made by the logging company of Fig. A and the oil base logs were made by the third logging company and the one represented in Fig. B. As may be seen, the logs correlate very well. The apparent reversal of the third curve of Fig. C, Curve Set No. 1, at approximately 5920 ft seems to be a peculiarity of the logging method in this particular zone since water base logs in this zone appear to have similar tendencies.

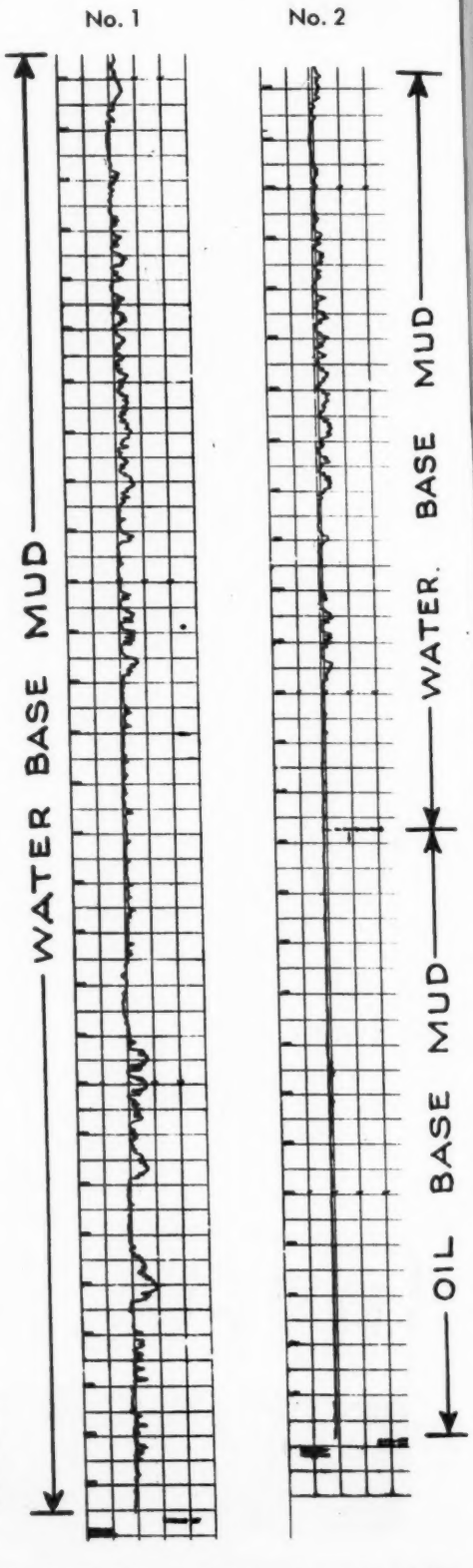
● **Effect of oil base vs. water base on size of drilled hole.** As mentioned before, an oil base mud with a zero fluid loss is an excellent medium for combating hydrous disintegrating or heaving shale and because of these very excellent plastering properties and the thin mud cake involved a "to gauge" hole is the ordinary result achieved with this type of drilling fluid.[1]

Fig. D shows two caliper logs run on comparative wells in a Texas field. Curve No. 1 is for a well drilled with water base mud and Curve No. 2 is for a well that was completed with oil base mud. In this particular field a running shale condition exists and washouts are com-

TABLE 2—Fig. 8
STATE—Colorado

	Offsetting wells	
	Oil base	Water base
Initial production:		
Bbl per day (net)	427	345
Cut	Clean	?
Flow bean, in.	¼	¼
Later production:		
Months later	No information available.	
Bbl per day		
Cut		
Flow bean		
Bottom hole pressure, psi	1900-2700	1900-2700
Producing zone interval, ft	60-600	60-600
Type of producing zone	Tight sand	Tight sand
Approx. permeability: max. 24 md. min. 0.8 md. Avg. for 13 wells)	11 md	11 md
P. I.	0.899	0.746
Remarks:	P.I.'s are average for 22 water base wells and 10 oil base wells.	Initial production is average for 29 water base wells and 21 oil base wells. Most of the water base wells were shot whereas the oil base were not.

FIG. D



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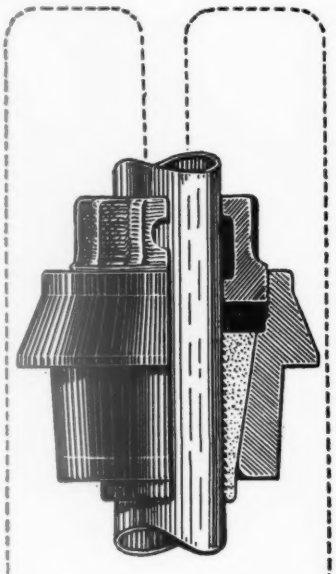

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TABLE 2—Fig. 9

STATE—Texas

	Offsetting wells				
	Oil base			Water base	
Well	A	B	C	D	E
Initial production:					
Bbl per day	102	92.4	106	38.6	37.2
Cut, per cent	?	0.2	?	0.1	?
Tubing pressure, psi	375	380	210	70	75
Casing pressure, psi	200	0	50	600	800
Flow bean, in.	5/32	9/64	6/32	6/32	5/32
Gas-oil ratio	427	378	298	362	526
Later production:					
Months later	No information available.				
Bbl per day					
Cut					
Flow bean					
Bottom hole pressure					
Producing zone interval, ft					
Type of producing zone	Sand and sandy shale	Sand and sandy shale	Sand and sandy shale	Sand and sandy shale	Sand and sandy shale
Approximate permeability, md	50	50	50	50	50
P. I.	No information available.				
Remarks: Bottom hole pressure for all wells approximately 2170-2200 psi.	Wells flowed immediately upon displacing oil base mud with crude oil.			Well had to be swabbed.	Well would not flow. After jetting with gas several weeks, began to flow.

mon. The operator stated that all water base well caliper logs were approximately the same as Curve No. 1. While completing the hole with oil base (Curve No. 2) this running shale condition, for all practical purposes, was unnoticed. As may be seen from the curves, the maximum hole size deviation with the oil base was 1½ in. and this deviation only occurred in one short section. With the water base mud, for the same footage of hole as drilled with the oil base in the comparable well, the deviation of hole size was almost 12 in. and occurred in various places, causing noticeable drilling hazards.

● **Well completions.** In Table 2 various offsetting and comparable oil base and water base mud wells have been compared for numerous fields in the United States. The names of the oil companies and the numbers of the wells have been deleted from the data in accordance with an agreement with the oil companies releasing the data. In general, the figures presented are self-explanatory. It will be noticed that the average permeabilities of these production zones range from 1 millidarcies to 3000 millidarcies and the productivity indexes range up to 250. The fields shown are not in the following order, but include Wilmington, California; Elk Hills, California; Orcutt, California; Coles Levee, California; Cymric, California; Rangely, Colorado, and Charlotte, Texas. Information could not be obtained for adequate presentation at this time for comparisons from other parts of Texas, New Mexico, Louisiana, Kansas, Oklahoma, Pennsylvania, or South America, due to lack of data or company policy regarding such release, but the data presented does indicate a very definite trend.

● **Conclusions.** To obtain the maximum productivity from oil or gas wells, the producing zones should be drilled or cored with a good oil base mud so that these producing zones will not be water blocked or mudded off.

In order to thoroughly fulfill the optimum possible properties to be derived from an oil base drilling fluid, it should be made from the proper materials and mixed with the correct type of oil for its base.

With proper supervision and cooperation wells can be completed with oil base mud for little more actual cost than is involved were conventional water base muds used. If the cost of oil base mud were several times higher than it is now, results show that this cost would be warranted.

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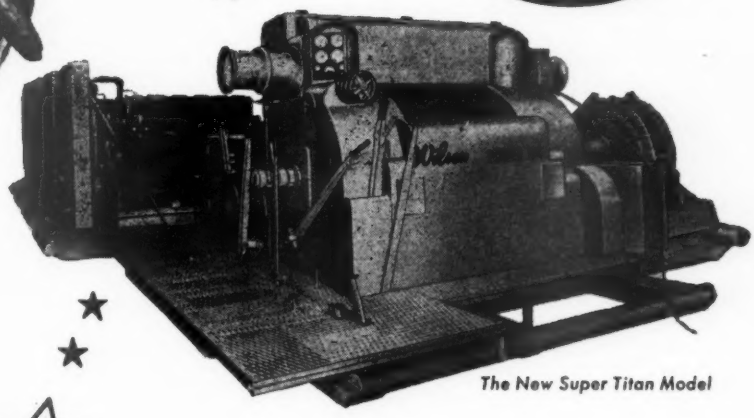

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Testing of drilling fluids*

By GEORGE R. GRAY†

THE tests that are commonly made to evaluate drilling fluids by the measurement of certain properties of the mud and mud filtrate are discussed in the paper. These tests will be made on a native mud from a well in East Texas.

The evaluation of the physical properties of the mud will be made according to "Recommended Practice on Standard Procedure for Testing Drilling Fuids," API Code No. 29 (Second Edition, July 1942).‡

● **Density.** Code No. 29 states, "Mud weight shall be determined by the use of any accurate instrument for determining specific gravity or density of fluids." Two instruments are in common use: the Hydrometer and the Mud Balance.

● **Hydrometer.** The Mudwate Hydrometer (Fig. 1) consists of an aluminum float spindle with calibrated stem, a detachable Bakelite cup, and metal carrying case. As with any other measuring device, the Mudwate Hydrometer must be used with a certain degree of care if accurate readings are to be obtained. There may be some variation in the readings because changes in temperature of the water in the bath cause changes in the equilibrium position of the float. Accuracy of the Hydrometer may be assured by maintaining the water in the outer container at the temperature at which the float was calibrated, or suitable corrections can be applied to compensate for changes in density of water with temperature.

Various combinations of graduations are available. These include a three-scale combination of pounds per square inch per 100 ft of depth (API density), specific gravity, and either pounds per gallon or pounds per cubic foot. Two-scale combinations include API density and either pounds per gallon or pounds per cubic foot.

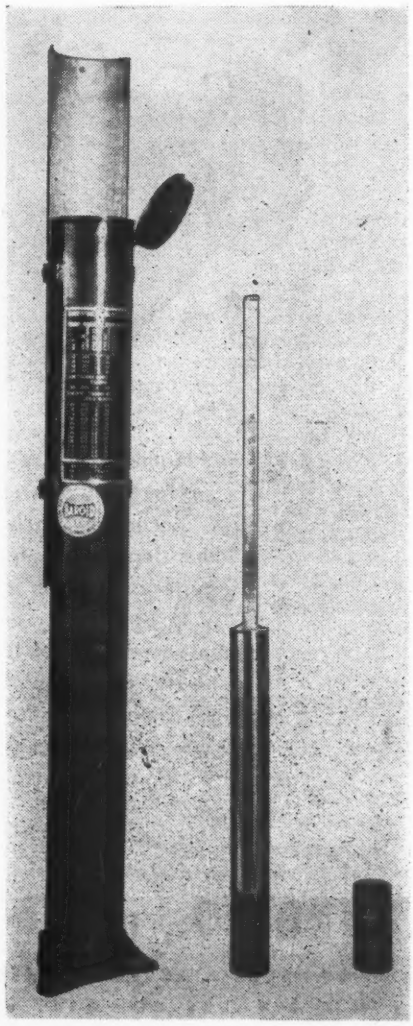
● **Procedure.** To use the Hydrometer, the cup is detached from the float stem by a turn to the left and is filled with the mud to be tested. The cup is replaced and the excess mud clinging to the instrument is wiped away. The carrying case is filled with water and the spindle is floated therein. The weight of the mud determines the depth to which the float stem sinks. The reading at the water level as the stem floats free gives the density of the mud in the particular units of calibration—in this instrument, in lb per gal and lb per sq in. per 100 ft of depth.

To check the accuracy of the Hydrometer, the cup occasionally should be filled with fresh water and a reading made. Water weighs 8.33 lb per gal or 43.3 psi per 100 ft of depth. If variance is noted, either recalibrate the instrument by adding or subtracting shot from the interior of the float stem, or adjust the readings according to the variance.

● **Mud Balance.** The Mud Balance is shown in Fig. 2. It consists principally of a base and graduated arm with cup, lid, knife edge, rider, and counterweight. The constant volume cup is affixed to one end of the graduated arm, which has a counterweight on its opposite end. The cup and arm oscillate in a plane perpendicular to the horizontal knife edge, which rests upon the support, and are balanced by adjusting the slide on the arm.

The arm is graduated in pounds per square inch per 100 ft of depth and pounds per gallon, or pounds per square inch per 100 ft of depth and pounds per cubic foot. A metal carrying case is available that holds the balance intact and in working position with the base of the instrument secured to the case. It also acts as a protection against wind, which may tend to disturb the natural oscillation of the sensitive balance during a test.

FIG. 1. Hydrometer.



The Mud Balance is very durable, having no parts that can be broken easily. Results are not affected materially by changes in temperature. The arm with cup provides a convenient dipper for taking a sample of mud.

● **Procedure.** To operate the Mud Balance, the lid is removed and the cup is filled with the sample to be tested. The lid is replaced and rotated until firmly seated, thus expelling the excess mud through the vent hole, Any mud adhering to the exterior of the instrument is either washed or wiped off. Next the balance arm is placed on the base with the knife edge resting on the fulcrum. The slide is moved until the instrument is in balance, which may be determined either by the level on the arm or by noting the position of the balance arm with respect to the base. The density of the mud in the cup is then indicated by the reading at the left-hand edge of the rider.

The balance in use here has the arm calibrated in pounds per gallon and in pounds per square inch per 100 ft of depth.

Density units in ordinary use are related as follows:

Psi/100 ft	Lb/gal	Lb/cu ft	G/cc
1	0.193	1.44	0.023
5.19	1	7.48	0.12
1.44	0.13	1	0.16
43.3	8.34	62.4	1

● **Viscosity.** Viscosity is a measure of the internal resistance of fluid to flow; the greater the resistance, the higher the viscosity.

Neither of the instruments in common use is entirely satisfactory for the measurement of viscosity of drilling mud.

● **Marsh Funnel Viscosimeter.** The Marsh Funnel Viscosimeter is used on almost every well for routine viscosity determinations. Its design conforms with the cut shown in Fig. 3. The funnel is 6 in. in diameter at the top and 12 in. long. An 8-mesh screen across the top serves to remove foreign matter from the mud to be tested. Each instrument is neatly finished inside to allow free flow of the mud, and is tested to insure accuracy. The handle has been so designed that the funnel can be secured in an upright position ready for use.

The funnel should be checked periodically with water. The funnel should give a reading of 26 ± 0.5 sec for fresh water at 70 F ± 5 F, the conditions of the test being as set forth below.

*Presented at the Drilling Fluids Conference, Texas A&M College, College Station, Texas, May 13-15, 1946.

†Manager Houston Laboratory, Baroid Sales Division, National Lead Company.

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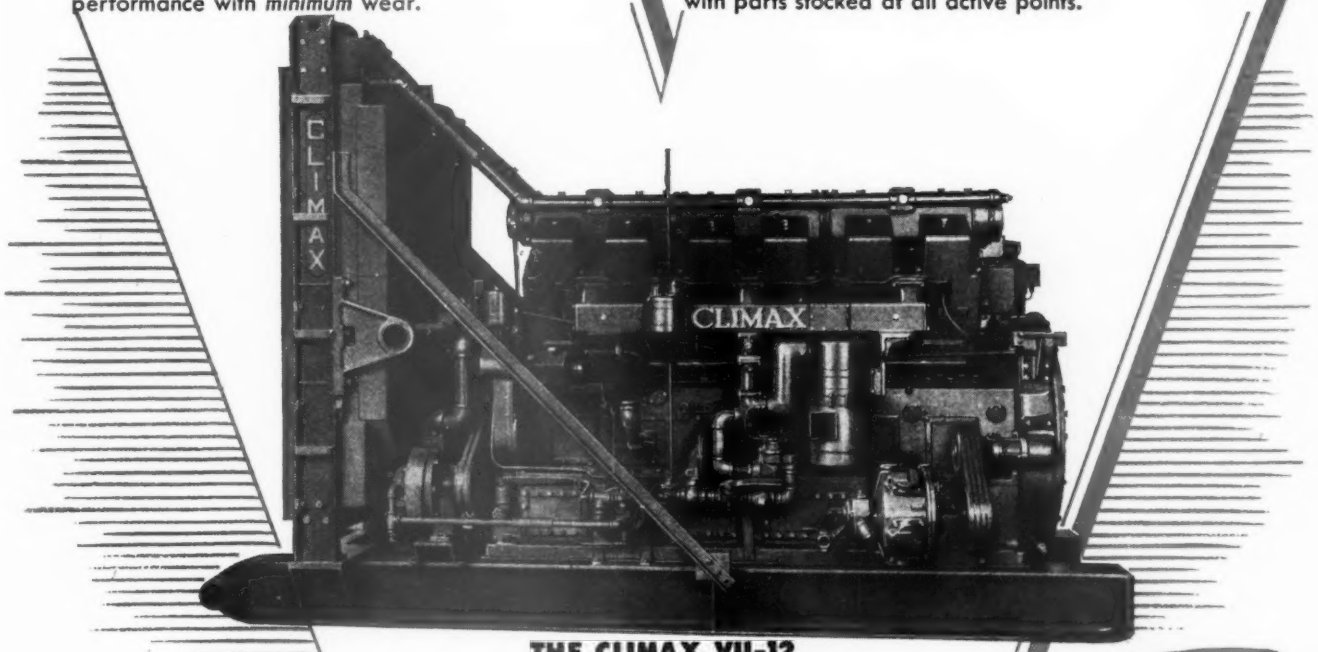

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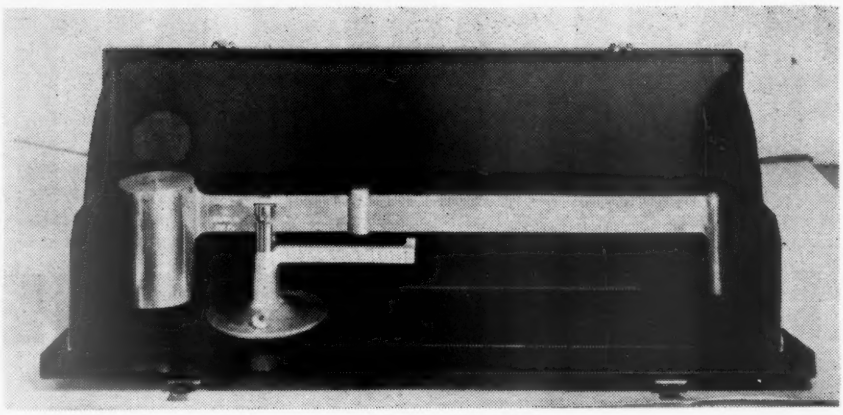


FIG. 2. Mud balance and carrying case.

● **Procedure.** The mud sample is poured through the screen until the fluid level reaches the bottom of the screen, which level represents a volume of 1500 cc. A finger is held over the orifice to prevent the mud from flowing while filling the funnel. When 1500 cc of mud have been placed in the funnel, the mud is allowed to flow into the receiver, measuring the time in seconds from the instant flow begins until the instant mud fills the receiver to the 1 qt level.

The viscosity determination is made immediately after taking the sample from a point in the circulation system where the mud is subject to violent agitation, such as just after passing through the mud screen. The results are reported in seconds.

● **Stormer Viscosimeter.** Within recent years, the Stormer Viscosimeter has come into general use in the field by mud engineers. The construction of the instrument is such, however, that it has not been practical to place a Stormer Viscosimeter on each rig to be operated by members of the drilling crew. With the Stormer Viscosimeter, viscosity is measured under conditions of flow and the determination is not affected materially by the density of the mud. It has the further advantage of providing a means of measuring gelling properties of the mud, as will be discussed later.

The Stormer Viscosimeter, shown in Fig. 4, consists essentially of a spindle that is rotated in a test cup by a pair of gears driven by a falling weight. The rotation of the spindle is indicated by a revolution counter.

● **Procedure.** The mud to be tested, screened free of any coarse materials, is thoroughly agitated and immediately thereafter is poured into the test cup to such level as to submerge the inner vanes completely. The cup is placed in the water bath and this whole assembly is pushed upward as far as it will go on the support rods and is secured with the set screw. The spindle is made free to rotate by releasing the brake situated on the gear case. The mud in the test cup is agitated by the operator revolving the spindle by turning the small crank on the line winder. Then metric weights are attached to the plumb line until the spindle is made to revolve at a rate of 600 rpm, as determined by the Stormer revolution counter and a stopwatch. By means of a calibration chart accompanying each Stormer Viscosimeter, the weight in grams required to achieve this rate of shear is converted into centipoises. Readings are recorded as centipoises determined by the Stormer instrument at 600 rpm.

● **Shear or gel strength.** The gel strength of drilling mud is a measure of the minimum shearing stress necessary to produce slip-wise movement, and, is a property of major importance in determining the satisfactory performance of a mud.

The instruments used to measure gel strength are not entirely satisfactory.

The Stormer Viscosimeter described above (Fig. 4) affords a means of measuring gel strengths over a wide range and is especially useful in the evaluation of chemical thinners.

● **Procedure.** The mud sample is prepared and placed in the instrument in the same manner as for measurement of viscosity. Whether or not a viscosity reading is taken, the mud in the cup is agitated by rapidly rotating the spindle for a few seconds just prior to the measurement of initial gel strength because the gel strength of most muds increases rapidly during the first few seconds after agitation has ceased. The initial gel strength measurement is made by determining the minimum weight required to effect a movement of approximately one-quarter revolution of the spindle after the brake is released. Weights are added in small increments by looping onto the string—the mud being thoroughly agitated after each addition—until the requisite rotation is obtained. The total weight in grams required to obtain this rotation is reported as the initial gel strength.

A second gel strength determination is made after the mud in the cup has been allowed to remain quiescent for ten minutes after the initial gel strength observation. Additional driving weights are added to the line and the brake is released. If no rotation of the spindle occurs, the brake is set again, more weight is added to the line, and the brake is released again. This process is repeated until the minimum weight required to cause rotation is found. This weight is reported as the 10-min gel strength. If more than one minute is required by the operator to determine the weight required to break the gel, the mud should be agitated in the cup and the test repeated.

● **Shearometer.** The Shearometer has been used in California fields for several years but has had only a very limited use in other areas. The Shearometer (Fig. 5) consists of a thin duralumin tube 3.5 ± 0.1 in. long, 1.4 ± 0.05 in. ID, and weighing 5 ± 0.1 grams.

The mud to be tested is agitated vigorously before the Shearometer is placed very gently on a quiescent surface of the mud and is allowed to sink vertically until the cylinder comes to rest. The depth of penetration of the tube is measured with a suitable scale, which is provided as an integral part of the in-

FIG. 3. Marsh funnel viscosimeter and measuring cup.

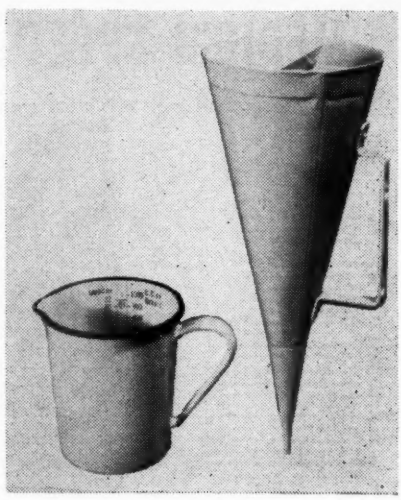
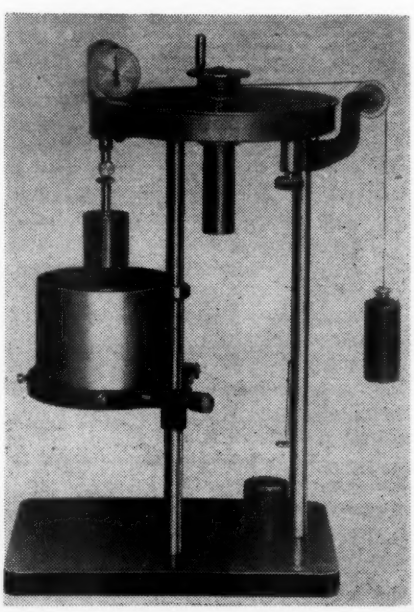


Fig. 4. Stormer viscosimeter.



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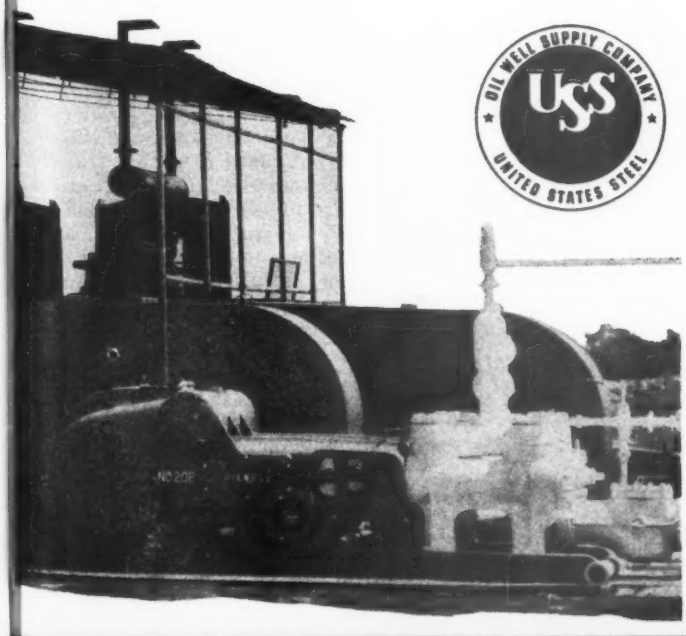

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strument. This scale is calibrated to read directly in pounds per 100 sq ft. The range is from 3.0 to 70.0 lb per 100 sq ft. Alternatively, the shear strength of the mud may be calculated from the following equation:

$$\text{Shear in lb per 100 sq ft} = \frac{174WL - WUX}{2.42 \times 3.14 \times DLX} \times 100$$

Where:

X = penetration, in.,
L = length of tube, in.,
D = diameter of tube, in.,
U = density of mud, lb per cu ft,
W = weight of Shearometer, lb.

The results are reported as shear strength in pounds per 100 sq ft. If the Shearometer is immersed completely the shear strength of the mud may be reported as zero, and if the Shearometer does not sink, the shear strength may be reported as too high for determination.

The shear strength also may be measured after any definite period of quiescence following agitation, in which case the time of quiescence is reported together with the shear strength.

● **Filtration and wall-building properties. Low-pressure filter press.** The wall-building or filtration property of mud is determined by means of a filter press, of the type shown here (Fig. 6). The filter press consists of a screw press frame and filter cell or mud cylinder assembly. The mud cylinder has an internal diameter of 3 ± 0.07 in., the resulting filtration area being 7 sq. in. The top of the cell is fitted with a gasket and a machined cap that has a small hole for admission of a pressure medium. The bottom of the cell is closed by a sheet of filter paper (Whatman No. 50 or 52 or its equivalent) backed by a wire screen and a bottom cap with necessary gaskets to provide an effective seal.

The filtration is carried on at a pressure of 100 ± 5 pounds psi. The pressure is supplied by compressed air or nitrogen, or any other adequate means of maintaining constant fluid pressure. We shall use a small cylinder containing nitrogen compressed at 1800 psi and equipped with a pressure regulator and bleeder valve. The pressures in the reservoir cylinder and in the filter are measured by gauges on the regulator assembly.

● **Procedure.** The temperature of the mud is determined prior to the test and reported as temperature of the run. For standard comparisons, a temperature of 100 F ± 5 F is recommended; however, other convenient temperatures can be used.

In assembling the apparatus, the gasket, wire screen, filter paper, and cylinder are placed on the bottom cap. Sufficient mud is poured in to fill the cell within 1 in. of the top. The top cap with gasket are placed on the reservoir cylinder, the screw press tightened, and the pressure applied as rapidly as possible. In order to avoid the possibility of damaging the regulator or the filter press, note carefully the sequence of operations in applying pressure to the filter cell. First, observe that the bleeder valve is open and the adjusting "T" screw on the regulator is unscrewed. Second, the valve on the nitrogen cylinder is opened about one-half turn. Third, the bleeder valve is closed, and, finally, the adjusting "T" screw is turned until the low-pressure gauge registers 100 psi. With a graduated cylinder in place to receive the filtrate, the volume accumulating in 30 min is recorded as the filter loss expressed in cu cm. At the expiration of the 30-min test period, the valve on the cylinder is closed, the pressure is released through the bleeder valve, and the adjusting "T" screw is turned to the left until it is free. The cylinder and bottom plate are withdrawn from the press intact, the excess mud fluid is poured out, and the filter cake is removed from the bottom plate after the latter has been carefully separated from the cylinder. The filter cake is washed free of excess mud with a gentle stream of water and the thickness of the cake is measured. The filter cake thickness is reported in thirty-seconds of an inch. The texture of the filter cake is observed, i.e., whether flexible or brittle, slick or grainy, firm or soft. Any other qualities of the cake that may be indicative of the wall-building properties of the mud are noted.

● **Sand content.** Although API Code No. 29 describes three methods of determining sand content, only one method will be demonstrated because it is far superior to the other two in reliability of results and simplicity of equipment.

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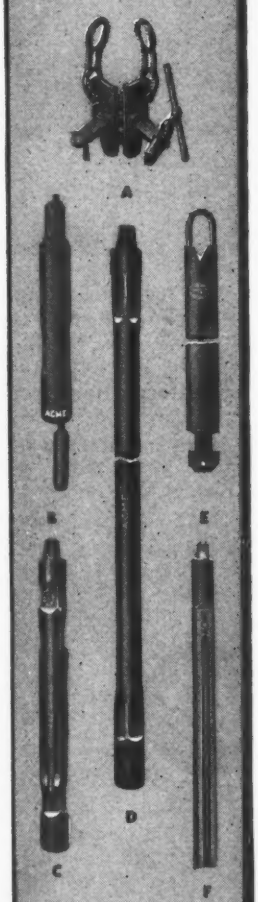

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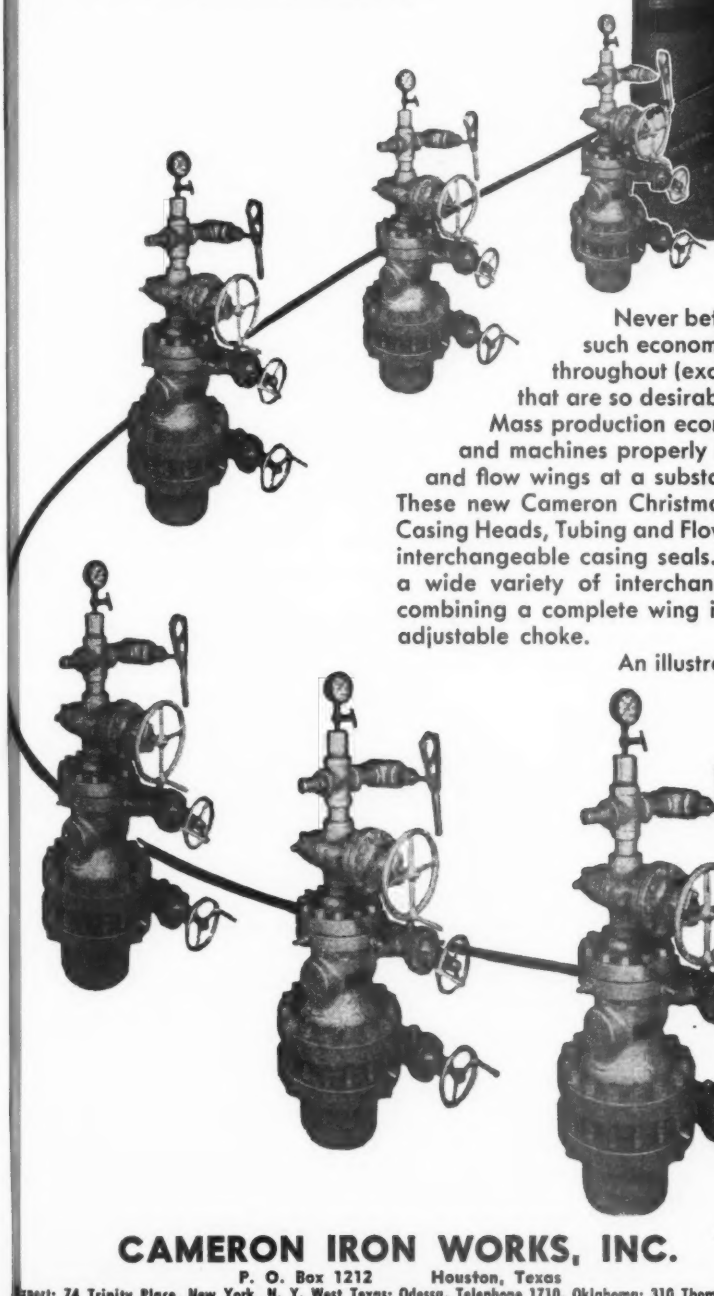

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● **Screen test.** The Baroid Sand Content Set, as shown in Fig. 7, consists of a 200-mesh sieve 2½ in. in diam, a funnel to fit the screen, and a glass measuring tube marked for the volume of mud to be added in order to read the percentage of sand directly in the bottom of the tube, which is graduated from 0 to 20 per cent.

● **Procedure.** To determine the percentage by volume of sand in a drilling mud with the Baroid Sand Content Set, the cylinder is filled with mud up to the indicated level. The tube is filled with water; the mixture is shaken and the diluted mud is poured into the sieve. More water is added to the tube and the sand on the screen is washed free of mud. The funnel is then placed on top of the sieve, the sieve and funnel are inverted, and the sand on the screen is washed into the measuring cylinder. The sand is allowed to settle to the bottom of the tube, the tube being tapped with the finger to secure uniform packing. The percentage by volume of sand is read from the graduated tube.

● **Hydrogen-ion concentration (pH).** Two methods of measuring the pH of drilling mud are in use: (1) the electrometric, employing the glass electrode, and (2) the colorimetric, using indicator paper. The electrometric method is more accurate than the colorimetric method but the equipment required is far more expensive and less sturdy.

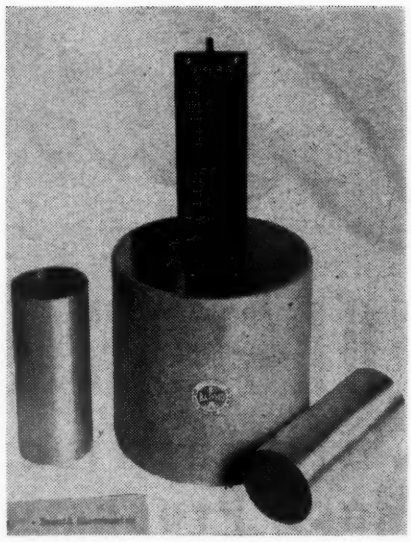

FIG. 5. Shearometer.

● **Glass electrode pH meter.** In the electrometric method of measuring pH, the electrical potential generated in the glass electrode system by the hydrogen ions in the drilling mud is amplified by an electronic amplifier and operates a calibrated meter that indicates the pH.

The glass electrode consists of a thin-walled bulb made of special glass within which a suitable electrolyte and electrode are placed. In this instrument (Fig. 8) the internal electrode is a silver-silver chloride-chloride buffer solution. The glass electrode is sealed to insure stability and is provided with an insulating sleeve. The reference electrode is a saturated calomel cell. Electrical connection with the mud is established through a saturated solution of potassium chloride contained in the tube surrounding the calomel electrode.

● **Procedure.** After making the necessary adjustments to put the amplifier into operating condition, the electrodes are immersed in a buffer solution of known pH and the meter is adjusted to read that value. The electrodes are removed from the buffer solution, washed gently, wiped dry, and placed in the mud. The meter reading then indicates the pH of the mud.

Detailed instructions for the operation and maintenance of the pH meter are supplied with the instrument.

● **pH test paper.** The pH test paper is impregnated with dyes of such nature that the color of the paper is dependent on the pH of the medium in which it is placed. Comparison of the paper with a standard color chart affords a means of estimating pH. The pH test paper is contained in a small plastic dispenser having the color chart on the side. Test papers are supplied in the wide-range type (1-11), with which the pH can be estimated to the nearest full unit, and the short-range paper, each roll of which covers a range of about two units and permits the estimation of pH to 0.25 unit.

● **Procedure.** The pH test paper is placed on the surface of the mud and after the liquid has wetted the paper

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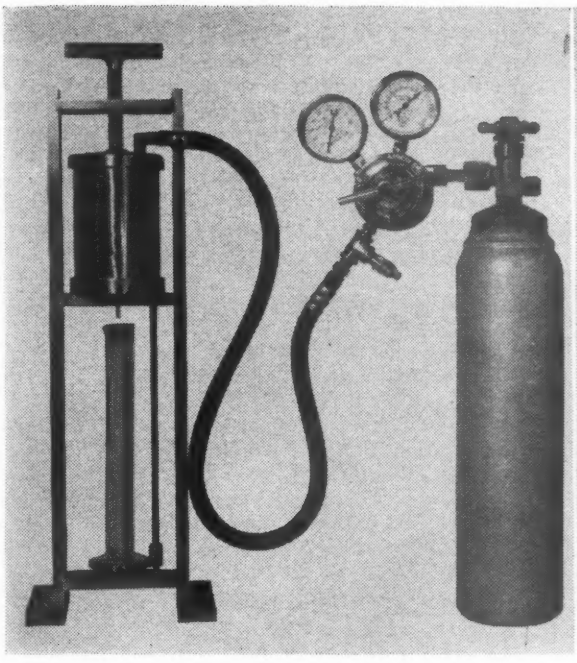


FIG. 6. Low pressure filter press.

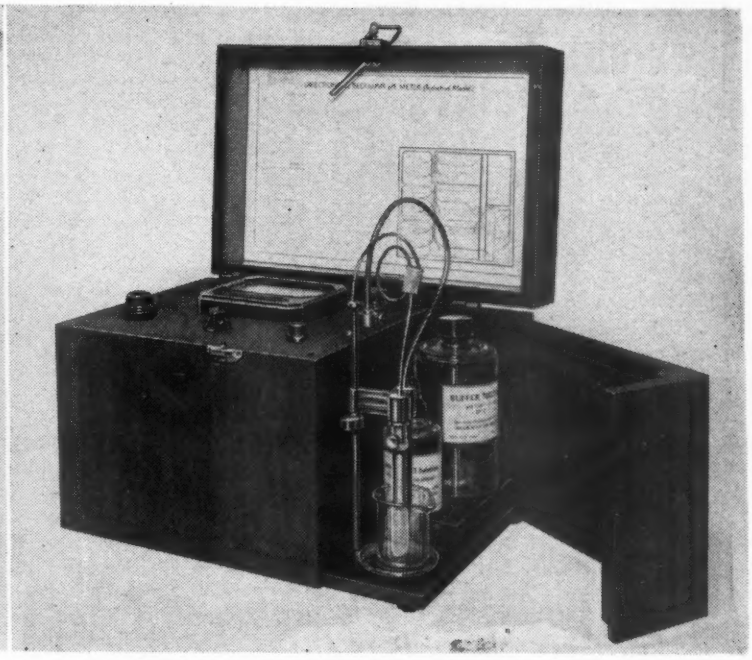


FIG. 8. pH meter.

(about 30 sec) the color of the paper is compared with the color chart. The pH may be estimated to one unit if the wide-range paper is used, or to 0.25 unit using the short-range paper.

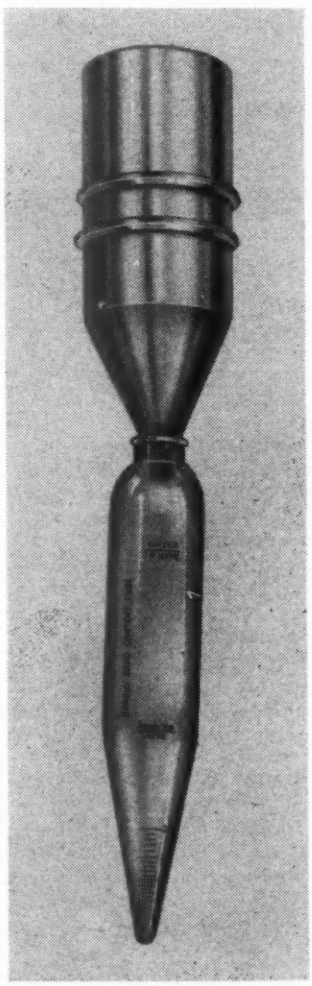
● **Results of tests on mud.** Before making any tests on the filtrate from the mud, let us survey the results of the tests which we have completed:

Weight, lb per gal	10.8
Weight, lb/sq in/100 ft	56
Viscosity, Marsh Funnel, sec	44
Viscosity, Stormer, centipoises	51
Gel strength, initial, grams	55
Gel strength, 10 min, grams	55
Filtrate, 30 min, cc	41.0
Cake thickness, 32nd. inch	8
pH	7.6

We note these objectionable properties: viscosity is somewhat high; the initial gel strength is equal to the 10-min gel strength; the water loss is too high and the cake is too thick. These faults point to the presence of some agent that has partially flocculated the colloidal clay fraction of the mud. It is reasonable to suspect salt or anhydrite. Tests will be made on the filtrate to determine what soluble substance may be responsible for the unsatisfactory characteristics of the mud.

● **Chloride content. Theory of test.** The mud filtrate containing the soluble chloride is titrated with a standard silver nitrate solution, using potassium chromate as an indicator. The chloride ion is precipitated by the silver nitrate as silver chloride. As soon as the chloride has been completely precipitated, further addition of silver nitrate will result in a red color due to the formation of silver chromate. This color change is taken as the endpoint. It is customary to report the results in terms of parts sodium chloride per million, although by this method all chlorides present in the filtrate (chlorides of magnesium and calcium, for instance, in addition to sodium) are determined and reported as equivalents of sodium chloride.

FIG. 7. Sand content set.



● **Apparatus and reagents.** Apparatus and reagents required are as follows:

1—Pipette, graduated, 1.0 ml.
1—Pipette, graduated, 10 ml.
1—Burette, automatic, 10 ml.
1—Casserole, 125 ml.
1—Stirring rod.
1—Funnel, 9 cm.
Filter paper.
Silver nitrate solution 1 ml = 0.01g. sodium chloride.
Potassium chromate indicator solution in dropper bottle.
Dilute nitric acid (3*N*) in dropper bottle.
Calcium carbonate, c.p. powder.
Activated charcoal, powder.
pH test paper.
Distilled water.

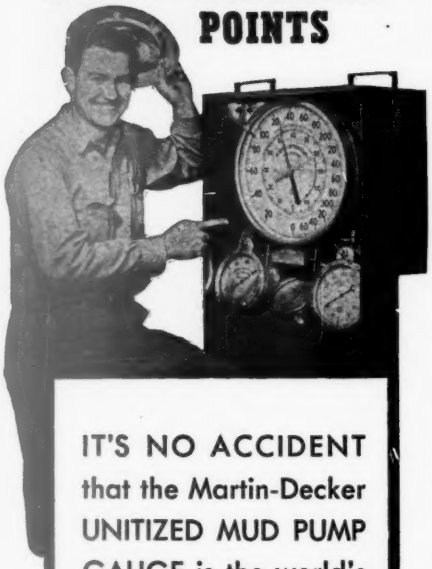
● **Procedure.** Measure accurately into the casserole such volume of filtrate from the mud as will require not over 10 ml of nitrate solution. (The quantity of filtrate taken may range from 10 ml for fresh-water mud to 0.3 ml for saturated salt-water mud.) Add about 50 ml of distilled water.

Measure the pH of the diluted sample. If the pH is above 9, add a few drops of dilute nitric acid, stir, and then add enough calcium carbonate to leave a slight excess undissolved after stirring. Add five drops of potassium chromate solution to the neutral solution. Add silver nitrate solution slowly while stirring continuously. The end point is reached when the color changes from yellow to an orange-red, which persists for 30 sec. The addition of more silver nitrate will produce a bright red color, which shows that the endpoint has been passed.

Record the number of ml of silver nitrate used in reaching the end point. Then, ppm salt (NaCl)

$$= \frac{\text{ml silver nitrate}}{\text{ml sample}} \times 10{,}000$$

WEIGHT INDICATOR POINTS



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If the mud filtrate is colored with tannin to such an extent that the endpoint cannot be seen in the solution after diluting and neutralizing as above, another portion of the filtrate is treated to remove the coloration as follows: To the measured filtrate, add 3*N* nitric acid in sufficient amount to change the color from red to tan. Add about 0.1 g of special activated charcoal, mix thoroughly and filter. If the first few drops of filtrate are not clear, add a little more filter. Wash the charcoal on the filter charcoal and return the mixture to the paper with about 50 ml of water. Add sufficient calcium carbonate to the filtrate to neutralize the acid. Titrate with silver nitrate in the usual way.

● **Calcium content (soap hardness). Theory of test.** The standard soap-hardness test commonly employed in water analysis can be used to estimate the calcium content of mud filtrate. The test is based on the titration of the dissolved carbon calcium and magnesium salts with a standard soap solution. Precipitation of calcium and magnesium soaps will occur and no lather will result until sufficient soap has been added to precipitate the calcium and magnesium. Further addition of soap will cause formation of a lather, which indicates the endpoint.

In conformity with standard practice of reporting results of water analysis, the hardness is expressed as ppm calcium carbonate, although the soluble calcium and magnesium salts responsible for the hardness may be sulphate, chloride, or bicarbonate.

● **Apparatus and reagents.** Apparatus and reagents required are as follows:

1—Bottle, glass stoppered, 250 ml.
1—Burette, automatic, 10 ml.
1—Pipette, graduated, 10 ml.
1—Cylinder, graduated, 50 ml.
Standard soap solution,
1 ml = 1 mg $CaCO_3$.
Distilled water.

● **Procedure.** First, determine the "lather factor" for the soap solution and the distilled water to be used. To 50 ml of water in the bottle, add 0.3 ml of soap solution, place the stopper in the bottle and shake vigorously. If a lather is formed, lay the bottle on its side. If the lather remains continuous over the entire surface of the water for 5 min, the endpoint has been reached. If the lather breaks in less than 5 min, add soap solution in increments of 0.2 ml, followed by shaking and waiting as before, until a stable lather is formed which persists for 5 min. The quantity of soap solution used is the "lather factor." The lather factor is usually 0.3 to 0.5 ml. The lather factor need be determined only once for each batch of soap solution and distilled water.

To determine the calcium (and magnesium) content of the mud filtrate, place 10 ml of filtrate in the bottle and add 40 ml of distilled water. Run in soap solution equivalent to the lather factor. Shake vigorously. If a permanent lather forms, the hardness is "zero." If a stable lather is not formed, continue adding 0.2 ml of soap solution at a time, shaking the bottle after each addition, until the endpoint is reached. Care should be taken that the endpoint is reached as occasionally a lather is obtained that will break when more soap solution is added. This false endpoint is caused by magnesium salts but has no quantitative significance. To make certain that the endpoint has been reached, read the burette after the titration apparently is finished and then add 0.5 ml more. The lather will disappear if the endpoint was a false one.

If over 10 ml of soap are required for the titration, repeat the test using a smaller volume of filtrate. Dilute to 50 ml with distilled water and titrate as before.

Hardness, as calcium carbonate:

$$\text{ppm} = \frac{(\text{ml soap solution} - \text{ml lather factor})}{\text{ml sample}} \times 1000$$

● **Results of tests on filtrate.** Using Using 10.0 ml of filtrate, 1.2 ml of silver nitrate solution were required. Then:

$$\text{salt, ppm} = \frac{1.2 \times 10{,}000}{10.0} = 1200$$

which is not high enough to account for the objectionable properties of the mud.

Using 5.0 ml of filtrate, 8.5 ml of soap solution gave a permanent lather. Then:

Hardness, as $CaCO_3$, ppm =

$$\frac{(8.5 - 0.3) \times 1000}{5.0} = 1640$$

We have here an explanation for the observed properties of the mud. Hardness in excess of 200 ppm indicates the presence of soluble salts of calcium or magnesium, or both, in sufficient concentration to affect the properties of the mud. In this instance, the clay fraction has been flocculated by anhydrite from the formation drilled.

● **Bibliography.** Papers listed below provide the basis of the standard methods now used and describe some special instruments and methods that have been utilized in evaluating drilling fluids.

1. "The Effect of Formation Permeability on the Plastering Behavior of Drilling Mud Fluids," H. T. Byck, *API Drilling and Production Practice, 1940*, 40.
2. "Effect of Temperature on Plastering Properties and Viscosity of Rotary Drilling Muds," H. T. Byck, *AIME Transactions 136*, 165 (1940). Also in *Petroleum Technology*, November 1939.
3. "Drilling Fluid Viscosimetry," W. T. Caldwell, *API Drilling and Production Practice, 1941*, 104.
4. "Study of Some Phases of Chemical Control in Clay Suspensions," A. D. Garrison and K. C. ten Brink, *AIME Transactions 136*, 175 (1940). Also in *Petroleum Technology*, November, 1939.
5. "Evalution of Rotary Drilling Muds," P. H. Jones and E. C. Babson, *API Drilling and Production Practice, 1935*, 22.
6. "Field Control of Drilling Mud," P. H. Jones, *API Drilling and Production Practice, 1937*, 24.
7. "Methods of Determining the Filtration Characteristics of Drilling Muds," D. H. Larsen, *The Petroleum Engineer*, September, November, 1938. Also in *Drilling Mud*, May 1938.
8. "Evaluation of Filtration Properties of Drilling Muds," M. Williams and G. E. Cannon, *API Drilling and Production Practices, 1938*, 20.
9. "Radial Filtration of Drilling Muds," M. Williams, *AIME Transactions, 136*, 57 (1940). Also in *Petroleum Technology*, November, 1939.
10. "Standard Methods of Water Analysis," 8th. Ed., New York, American Public Health Association (1936).

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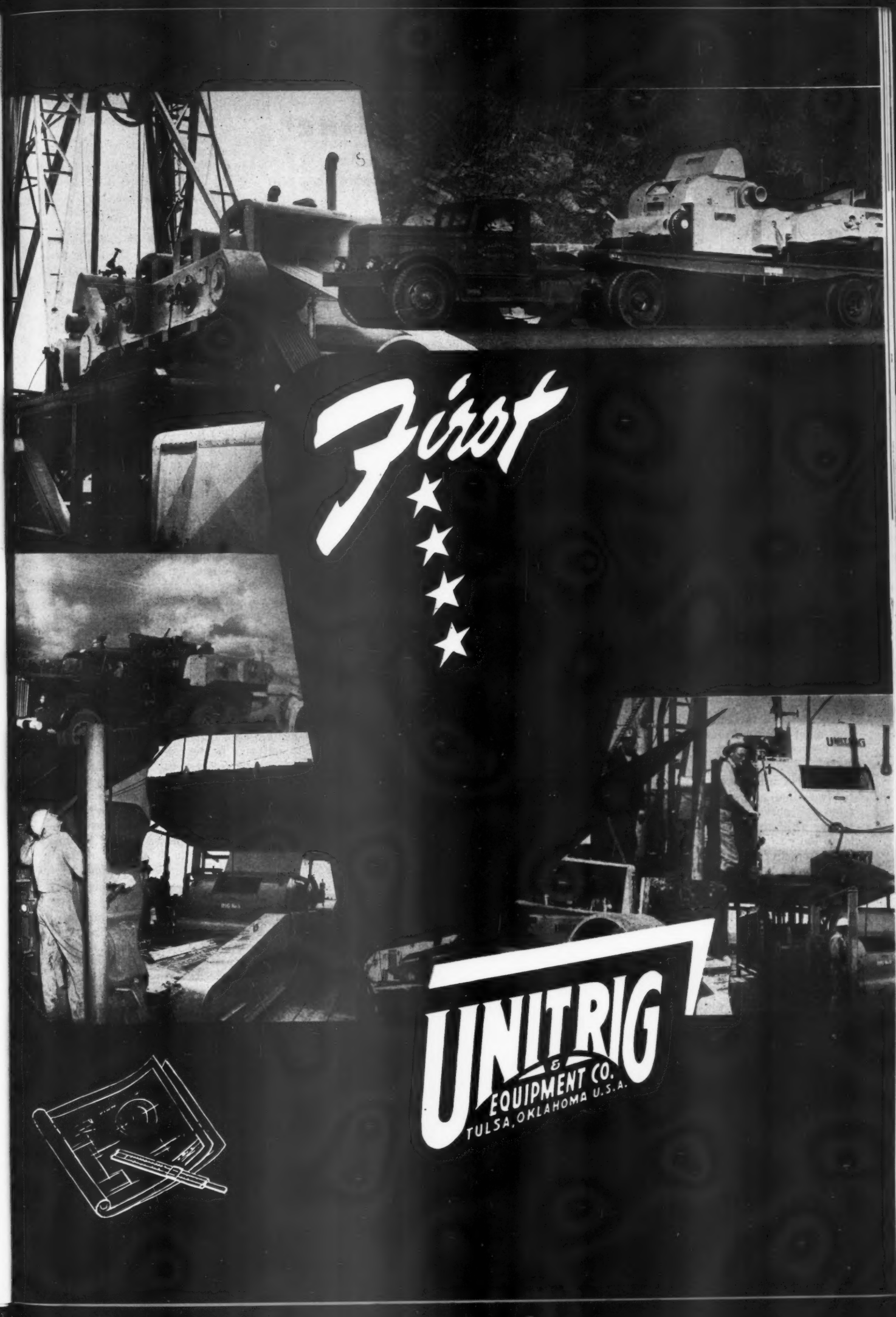
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Marble shooting*

By J. GORDON BURCH, Burch Agate Torpedo

OPERATORS have long recognized the difficulty of maintaining profitable production until the oil and gas in the formation has been exhausted. Unquestionably it has always been one of the principal problems production men have had to deal with.

Five years after the Drake well was completed, Col. E. A. L. Roberts introduced the idea of shooting oil wells for the purpose of relieving the surface of the oil producing sands from their encrustments of gypsum, salt, and slime. He believed that "the cessation of production is due to the sludge of oil and gumbo of mud which plugged the fissures leading from the well to the mother pool."[1] His first attempt was made with six pounds of powder in the once famous Ladies well in Pennsylvania and was successful. Col. Roberts became the father of oil well shooting and obtained a patent for the purpose of "raising wells from the dead."[2]

The idea that Col. Roberts gave to producers has grown until now it has become a general practice to use massive bulk shots of high explosives. Operators took the attitude that "if a little is good, more is better." As an operator I have come to know that this is not entirely true.

To measure the effectiveness of any treatment it is necessary first to examine the nature of the work to be done.

The surface of the pay section exposed in a well may become so effectively sealed off that oil cannot enter from the naturally porous oil bearing strata. This condition does not extend more than a quarter of an inch into the formation, but it is anchored firmly to the formation and is very difficult to remove. There are various forms of this encrustment. Paraffin is quite effective in choking a well. Most of the encrustments, however, are mineral, having their origin in the chemical action of gypsum and other salts present in the well. They embed themselves in the formation and build out from the wall of the well with a sleek, glossy, impervious substance.

The task then is to destroy this substance and to scale the walls to a depth of a fraction of an inch so as to expose again the natural formation. When this is done, no method of well treating can do more to increase production. No more oil can be produced from a well than the amount that flows to the bore through the natural formation, whether it migrates naturally or is moved by artificial production methods. In most productive wells, each day's production travels a greater distance to the well bore than any treatment could reach. I repeat, therefore; so far as well treating is concerned, the limit is reached when the surface of the pay section has been restored to its natural state.

If it were possible to lower a man to the bottom of the well bore, he could probably do in one day with a hammer and chisel all the work that is needed to scale away the congestion from the natural formation and restore the well to its maximum capacity. The amount of work needed to be done is after all not large, but nitroglycerin, powerful as it is, is not able to apply its energy efficiently to this particular piece of work when used in bulk form. The compactness and incompressibility of the earth at the depth of an oil well will not permit extensive blasting.

"In solid rock the chamber or cavity is the result of the dynamite explosion's burning or grinding off and forcing out through the bore hole small spalls and fine particles of the rock, and is not the result of compressing the surrounding rock walls."[3]

At detonation an explosive is converted partly into energy and partly into heat. The work accomplished by an explosive is the result of the energy exerted by expanding gases. If an explosive were confined where gases could expand none, all the energy of an explosive would be converted into heat. Where the space is limited as it is in a tamped shot, the amount of work the explosive can do is correspondingly limited. The larger portion of the energy in the explosive is wasted as heat. If confined within a limited space, the massive shot can perform no more than a fraction of the work of which it is capable. Knowledge of this fact is employed in all other industrial uses of explosive except in oil well shooting.

In a 500-qt shot of 100 per cent explosive there are 3,575,000,000 ft-lb of energy. This tremendous amount of explosive does no more than pulverize the wall of the well bore to a slight depth. When this pulverized formation is cleaned from the wall, the natural formation is exposed, but why should we pay for billions of foot-pounds of energy to obtain the results equal to one man-day of work.

In using columns of explosive much smaller than the well bore, as employed in our squib shots, the void between the explosive container and the bore defeats the effectiveness. The void cushions the shock of detonation, and the congested formation is not pulverized enough to free the walls. The energy of the explosive in gaseous phase is dissipated along lines of least resistance into any breaks, bypassing all irregularities. The treatment therefore becomes little more than a brushing effect. The maximum effectiveness of a bulk shot is obtained by filling the hole with explosive.

Development of new explosives resulting from the war years may soon allow their use in oil-well shooting. Their action and power will still be ineffective, however, in doing a greater job at oil-well depths by reason of the fact that the weight of the overburden cannot be moved.

Simple cleaning methods have been found to be most practical. Any method of reconditioning—including the use of explosives—that makes it necessary to move in tools should be postponed so long as results from the use of heat or solvents give profitable production. Both are effective for a period of time in the earlier stages of congestion until it becomes so dense it is impenetrable. Then the encrustment must be attacked with enough severity to dislodge completely all the congested formation.

Regardless of the type of formation accumulated congestion on the walls of a well may be successfully removed by using explosive-propelled glass marbles. By utilizing the potential energy of a small amount of nitroglycerin, the walls of a well can be cleaned effectively and at a very low relative cost. Clean out time is much less, and the cost of the job is no more than a fraction of that where massive bulk shots are used.

The tool consists of two concentric fragile tubes. Heat-treated glass marbles, $\frac{5}{8}$ in. in diam, fill the annular space between the 3-in. outer tube and the $1\frac{5}{8}$-in. tube in the center that contains the explosive. The marbles harness the energy of the explosive absorbing and transmitting it uniformly. They are unharmed at detonation and are propelled uniformly outward from the explosive at a high velocity. They convert the greater portion of the energy of the explosive into work, which they perform by destroying the surface of the wall of the well.

The tool fires 242 marbles per linear foot into the congested face of the pay section. The marbles strike the formation with a penetrating energy equal to chiseling a $\frac{5}{8}$-in. hole through $\frac{1}{2}$-in. steel plate. When the increasing resistance of the formation stops penetration, the marbles disintegrate violently with a sunburst blast toward the center of the

*Presented at Spring meeting of Eastern District, American Petroleum Institute Division of Production, Pittsburgh, Pennsylvania, June 13-14, 1946.

1. *Coronet Magazine.* December, 1936, p. 174.
2. *Coronet Magazine.* December, 1936, p. 174.
3. *Dupont Blasters Handbook,* p. 108.

bore, cleaning all encrustations from the face of the pay formation.

This tool has been used effectively in more than 1000 wells. Regardless of the character of the formation or of the irregularities of the hole, the action of the tool is dependable. It is as simple as sandblasting.

Although primary interest shown in this tool has been in its ability to clean the face of the well bore thoroughly by removing congestion and permitting the well so treated to produce to its full capacity, other uses have been made of the tool with surprising results. Of equal value to its reconditioning ability are the results obtained in pipe shooting. The amount of explosive used has enough power to shred the pipe without junking the hole. It is, therefore, possible to shoot pipe without the damaging reaction that results when explosive alone is used. This function is valuable. The results give access to sealed production by rupturing and increasing the circumference of the pipe concentrically.

Salt water disposal and input wells become congested with solids. Formations tend to filter solids out of the fluids that pass into them. The marbles have been used effectively to remove this sheath from the face of the well bore. They have been used also in lieu of an underreamer in wells that have been rat-holed deeper to increase the size of the small hole drilled to accommodate liners. Desired sections of squeeze jobs have been reopened, underreamers started in drilled holes, and key-seated holes corrected. In all these and other jobs this tool has been used open and untamped without damage to casing and liners.

When it becomes necessary to clean a well, the simplicity and thoroughness of explosive propelled marbles will give the operators all the oil there is in place, positively and economically. When all congestion at the face of the pay section is eliminated, capacity production is the result.

When considering reconditioning costs, we cannot escape the fact that each well must assume the financial obligation of repaying the expense. The cost of any reconditioning job must be repaid by the increased production made possible by the treatment, and no operator can afford to spend more.

A few words cannot portray the motivating influence behind the development of this method of reconditioning, but it has been my desire to help our wells and to prevent premature abandonment. This tool was developed to provide a method of reconditioning some of my own marginal producers at a cost they could repay.

The low cost of this method cuts to a fraction the reconditioning costs on any well. Its most striking virtue, however, is found in the fact that its use makes possible the thorough reconditioning of many stripper wells that cannot be treated profitably by any other method.

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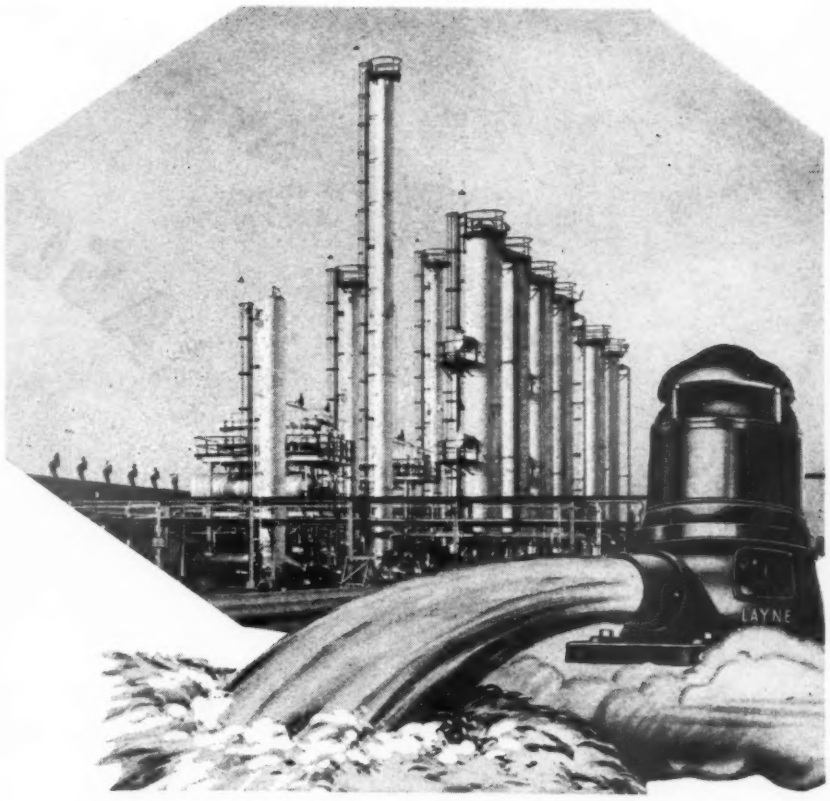

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History of reserves and production of natural gas and natural gas liquids in Texas*

By PERRY OLCOTT, Humble Oil and Refining Company

● **Abstract.** The natural gas and natural gas liquids reserves have been divided into three categories because of current producing and regulatory practices. These categories are (1) non-associated gas (free), (2) associated gas (gas cap), and (3) dissolved gas. The total reserves of these three categories in Texas as of January 1, 1946, were about 75 trillion cu ft, divided (1) 69 per cent, (2) 22 per cent, and (3) 9 per cent. The number and volume of natural gas discoveries have increased materially in recent years and the year-end reserve has increased steadily.

Natural gas liquids are defined as the liquids being recovered from the three categories of gas by current plant or field practices. The total natural gas liquids reserves in Texas were about 1.5 billion bbl with about 52 per cent in the non-associated gas, 21 per cent in the associated gas, and 27 per cent in the dissolved gas.

The gauged gas production in Texas in 1945 was about 2.9 trillion cu ft or a daily average of 79 billion cu ft. The natural gas liquids produced during 1945 in Texas were about 61.5 million bbl or a daily average of 168,000 bbl.

● **Introduction.** For the past several years, the subject of natural gas and natural gas liquids has become increasingly important. A variety of influences and factors have contributed: (1) Cycling operations have been found profitable; (2) as wells are drilled deeper, the industry has been finding more commercial gas reserves; (3) oil fields with sizable reserves are becoming more difficult to find; (4) recognition of the necessity of reducing gas wastage has become a major issue with the State regulatory bodies; (5) the Federal Power Commission has instigated hearings in an attempt to regulate sales price based on producing costs and to control the end use of gas; (6) the growing use of natural gas as a raw material for synthetics, plastics, and fuels has increased the demand; (7) the opposition of the coal industry and unions to the competition of gas in the fuel markets; (8) the stand of some of the members of State regulatory bodies to the exportation of gas from their states; (9) the increased demand for carbon black in the making of synthetic rubber products, etc.; (10) the oil companies' cooperation with the regulatory bodies in the conservation of gas has made it one of the most important studies of the day. There probably are several other reasons. The possibility of commercial sulphur from sour gases similar to that obtained from the plant at the McKamie field in Arkansas could be mentioned. This plant is now producing about 60 tons a day of sulphur from sour gas, although the plant was built in order to sweeten the gas for commercial uses and not to produce sulphur. The main point is that the industry is now interested in gas and its liquefiable products and probably will become more interested in the immediate future.

Gas is usually found incidentally or accidentally — incidentally when it is found dissolved in oil, and accidentally when it is found instead of oil. It is seldom that a wildcat well is drilled solely for gas. For this reason, in many cases when gas is discovered, the well is either shut-in until a market is found or is used for fuel to drill other wells in search for oil.

Natural gas was first used as a fuel in western China in about 200 A. D. to evaporate brines. It was first used as an illuminant in New York state in 1821. The first commercial pipe line was laid in 1883, from Murrysville, Pennsylvania, to Pittsburgh. The first gas compressed was in 1890 in the Murrysville field, when the gas was transported by high-pressure pipe lines. The long-distance transmission lines from the Southwest started in 1925 with the advent of oxy-acetylene welding and improved seamless carbon-steel pipe.

The natural gas reserves and contained liquids in Texas have been divided into three categories: (1) Non-associated gas or free gas not associated with oil in the reservoir; (2) associated gas which is gas overlying an oil reservoir as a gas cap; and (3) dissolved gas or the gas in solution in the oil in the reservoir, which is released when the oil is produced. The non-associated gas and the associated gas together make up what is generally called free gas, and the part of the associated gas produced with oil and the dissolved gas is called casing-head gas. These three categories were established because of the current conservation practices and the Railroad Commission regulations. All gas figures to be shown will be on a pressure base of 14.65 psia.

The non-associated gas represents about 69 per cent of the total gas reserves. This is the gas produced from gas wells in Texas, and in general the only restriction is that the production must be marketed and the allowable cannot exceed 25 per cent of the open-flow potential. Allowables have been set in only a few fields of this type to date. This non-associated gas is the gas generally produced through cycling plants or into gas pipe lines for fuel.

The associated gas, representing about 22 per cent of the total gas reserve, is restricted to cycling operations and those quantities produced with oil as casing-head gas. On October 20, 1944, the Texas Railroad Commission changed its Rule 6 to read that the amount of gas that could be produced from a gas well in a gas cap is limited to a volumetric displacement of oil and gas equivalent to a 2000:1 ratio on the highest oil allowable. Under this ruling, the oil allowables of high ratio wells are penalized, and the only way a gas cap can be utilized is to cycle the gas and strip the heavier hydrocarbons. For this reason, it is necessary to separate the *free* gas reserves into the part available for market and the part that can be cycled only.

The dissolved gas designation is the same as has been used for years and represents the gas liberated from solution in the oil as it is produced. This is the remaining 9 per cent of the gas and is generally produced through natural gasoline plants when the volume and yields are sufficient to warrant the construction of a plant. In fields where there are no plants, the dissolved gas is either used for fuel, compressed and put into gas

TABLE 1. State of Texas natural gas cumulative discoveries, production, and year-end reserves at five-year intervals, 1900-1945, inclusive.

Million cubic feet

	Cumulative discoveries				Production		Estimated year-end reserve
	Non-Assoc.	Associated	Dissolved	Total	Yearly	Cumulative	
Prior to 1901	—	—	5,462	5,462	650	650	4,812
1905	—	37,500	152,642	190,142	11,000	32,263	157,789
1910	200	37,500	158,201	195,901	8,000	69,163	126,738
1915	19,834	89,475	603,833	713,142	30,324	169,054	544,088
1920	30,962,510	432,675	1,055,125	35,450,310	80,019	416,080	32,034,230
1925	32,080,432	1,056,634	1,884,434	35,021,500	418,964	1,796,157	33,225,343
1930	32,974,393	2,612,177	5,850,947	41,437,517	967,880	5,611,280	35,826,237
1935	40,088,266	12,622,674	8,339,179	61,050,119	1,218,085	10,754,444	50,295,675
1940	60,890,446	18,525,529	11,114,939	90,530,914	1,523,650	17,470,863	73,060,051
1945	68,045,936	21,626,944	12,904,662	102,577,542	2,607,177	27,481,714	75,095,828

*Presented before American Association of Petroleum Geologists, Chicago, Illinois, April 2, 1946. Published in *AAPG Bulletin*, Vol. 30, No. 7, July, 1946.

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The yearly consumption of more than 3¾ trillion cu ft of natural gas is a weight of about 91,000,000 tons, or about the weight of the steel industry's annual output. Its heating value is that of 150,000,000 tons of coal.

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pipe lines, used for repressuring or gas lift or flared. It should be kept in mind that there is no material physical difference between these three gases. The distinctions are solely on the basis of their position in the reservoir as related to oil and whether in a single-phase or two-phase reservoir.

The history of the gas discoveries in Texas has been one of ever increasing volume. The accompanying tables show these discoveries and the relationship between the three categories. In these tables the total reserves of each field are credited to the year in which the field was discovered.

● **Natural gas discoveries by years.** Table 1 shows the cumulative discoveries by five-year intervals of the three categories of gas. Dissolved gas was first discovered in Texas in 1865 in the Nacogdoches field. Free gas and, in this case, associated gas was first discovered in the Petrolia field in North Texas in 1904. The first non-associated gas was discovered in Southwest Texas in the Gas Ridge field in 1912. In the early part of this century, gas discoveries in Texas were plugged and the rig was moved to another location or else the operator "let-her-blow" until the head was off and oil was produced. The dissolved gas discoveries increased, of course, with the discovery of oil and reached a peak in 1930 when the East Texas field came in. In that year a total of almost 2 trillion cu ft of dissolved gas was discovered. The associated gas discoveries had several peaks but reached a maximum in 1934 and 1935 when a total of about 8 trillion cu ft of associated gas was discovered. The most recent peak of purely non-associated gas discoveries was in 1939 when the Hugoton (Texas portion), Paradis, LaGloria, and Agua Dulce fields were discovered for a total of about 9 trillion cu ft; however, the largest volume of non-associated gas discovered was in 1920 when the Panhandle field was brought in. The gas in this field is classified as non-associated gas. The five-year period, 1935 to 1940, showed gas discoveries in Texas of almost 30 trillion cu ft or an average of 6 trillion cu ft a year. This is equivalent to the current production of the entire United States.

There has been a total of 2231 gas reservoirs discovered in Texas since beginning. In this count of reservoirs, there were 756 non-associated gas reservoirs, 508 associated gas reservoirs, and 967 dissolved gas reservoirs. The dissolved gas reservoirs were counted as fields instead of separate reservoirs. Southwest Texas has first place in non-associated and associated gas reservoirs with 426 and 262, respectively. The Texas Gulf Coast is second in both categories with 244 and 168 reservoirs, respectively. The greatest number of dissolved gas reservoirs is in North Texas where 298 fields have been found as compared to 282 in Southwest Texas and 188 in the Gulf Coast. The number of non-associated gas reservoirs found has materially increased in recent years. Twenty years ago in 1926 there were only 9 non-associated gas reservoirs, 10 associated gas reservoirs, and 46 dissolved gas reservoirs or oil fields found. In 1945 there were 148 non-associated, 51 associated and 102 dissolved gas reservoirs found. This is a complete reversal in the number of discoveries by categories in this 20-year period; however, the total number of reservoirs discovered in Texas by years has increased from a low of 32 in 1931 to a high of 307 in 1944 or almost ten times in 15 years. The year 1945 was very close to 1944 with a total of 301 reservoirs of all classes.

The average volume of gas discovered per non-associated gas discovery is 90 billion cu ft. The associated gas discoveries averaged 42 billion cu ft, and the dissolved gas discoveries averaged 34 billion cu ft. The State average for all discoveries of gas was 46 billion cu ft per discovery.

The production of gas was relatively small until about 1925 when production reached a billion cu ft a day as compared with the current rate of about 7 billion cu ft a day for the state. This is about 44 per cent of the estimated 16 billion cu ft a day produced in the United States.

With 15 projects completed, 10 under construction, and 44 planned, Texas will have 69 gas-conservation (casinghead gas) plants costing $127,000,000. The utilization and saving of condensable hydrocarbons in Texas started from zero and has now reached in excess of 200,000 bbl a day.

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This seven fold increase in gas production in Texas has been in a period of 20 years. Oil production has increased only five times in the same period. The estimated cumulative gas production since beginning is 27.5 trillion cu ft or about 27 per cent of the total gas discovered. In comparison, the oil discoveries have been depleted 43 per cent. This estimate of production includes all gas produced, gauged, and vented from oil and gas wells.

Gas reserves in Texas have been constantly increasing until they now exceed 75 trillion cu ft. In the last 5 years over 2 trillion cu ft have been added to these reserves notwithstanding a production of almost 10 trillion cu ft in the same period.

● **Natural gas discoveries by districts.** Table 2 shows that of the 102.6 trillion cu ft of gas discovered in Texas since beginning, 68 trillion or 66.34 per cent was non-associated gas, 21.6 trillion or 21 per cent was associated gas, and 12.9 trillion or 12.58 per cent was dissolved gas. Of this amount about 40 per cent of the total gas found was in North Texas. This is due primarily to the huge Panhandle gas field and the Texas part of the Hugoton field. The second most important gas area in Texas is the Gulf Coastal region with total discoveries of 24 trillion cu ft. Southwest Texas is third with 19 trillion cu ft, with East Texas fourth, and West Texas a poor fifth. Of the non-associated gas, North Texas, Gulf Coast, and Southwest Texas maintain the same order as the total, with Southwest Texas a close third to the Gulf Coast. The West Texas area has very little associated gas since the larger reserves are found as gas caps or associated gas. The Gulf Coast area takes the lead for associated gas with 9.9 trillion cu ft, with Southwest Texas and West Texas second and third. The West Texas area with its large oil reserves and gas-drive fields has discovered the largest volume of dissolved gas. The gas-drive fields produce not only the gas in solution with the produced oil but also the gas in solution with the oil that is left in the reservoir. The 3.7 trillion cu ft of dissolved gas in that district represents 29 per cent of the state total of dissolved gas. North Texas is second in dissolved gas discoveries, and East Texas is third. This relationship is not true of oil reserves. The East Texas area is first in ultimate oil reserves, but due to the low solution ratio (320) in the East Texas field, the volume of gas found was not as large in proportion. This lack of volume in the East Texas field is more than compensated by the yield of liquids, which is about 4 gal per M cu ft.

Table 2 also shows the volume of gas

TABLE 2. State of Texas cumulative natural gas discoveries by districts since beginning.

Million cubic feet

	Non-associated		Associated		Dissolved		Total	
	Total discovered	Per acre	Total discovered	Per acre	Total discovered	Per acre	State	Per acre
Gulf Coast	11,874,654	65.0	9,935,418	54.3	2,390,386	12.4	24,200,458	60.3
District, per cent	49.07		41.05		9.88		100.00	
State, per cent	17.45		45.94		18.52		23.59	
East Texas	7,424,780	21.9	1,791,442	24.1	2,432,084	10.3	11,648,306	20.0
District, per cent	63.74		15.38		20.88		100.00	
State, per cent	10.91		8.28		18.85		11.36	
Southwest	11,841,109	36.8	5,590,502	32.8	1,677,934	5.6	19,109,545	29.9
District, per cent	61.96		29.26		8.78		100.00	
State, per cent	17.40		25.85		13.00		18.63	
West Texas	158,075	4.2	3,040,076	18.1	3,747,476	5.7	6,945,627	9.8
District, per cent	2.28		43.77		53.95		100.00	
State, per cent	.24		14.06		29.04		6.77	
North Texas	36,747,318	16.3	1,269,506	6.4	2,656,782	5.2	40,673,606	14.6
District, per cent	90.34		3.13		6.53		100.00	
State, per cent	54.00		5.87		20.59		39.65	
Texas	68,045,936	21.7	21,626,944	27.3	12,904,662	6.8	102,577,542	20.0
State, per cent	66.34		21.08		12.58		100.00	

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TABLE 3. State of Texas gas reserve and proved gas acres as of January 1, 1946, by districts.

	Non-associated gas		Associated gas		Dissolved gas		Total		Avg. res. per surf. acre MMCF
	Prod. acres	MMCF reserve	Prod. acres	MMCF reserve	Prod. acres	MMCF reserve	Surf. acres	MMCF reserve	
Gulf Coast	182,602	11,320,209	182,681	8,807,120	193,174	1,435,925	401,051	21,563,254	53.7
District, per cent.		52.50		40.84		6.66		100.00	
State, per cent	5.82	21.90	23.05	53.33	10.19	20.81	7.84	28.71	
East Texas	338,685	6,683,124	74,055	1,111,444	235,630	1,336,080	581,721	9,130,648	15.7
District, per cent.		73.20		12.17		14.63		100.00	
State, per cent	10.80	12.93	9.35	6.73	12.43	19.37	11.36	12.16	
Southwest Texas	321,877	10,000,807	170,550	3,933,953	300,215	1,035,731	639,147	14,970,491	23.4
District, per cent.		66.80		26.28		6.92		100.00	
State, per cent	10.26	19.35	21.52	23.82	15.83	15.01	12.49	19.94	
West Texas	37,690	132,715	167,690	2,262,207	656,250	2,459,556	710,709	4,854,478	6.8
District, per cent.		2.73		46.60		50.67		100.00	
State, per cent	1.20	.26	21.16	13.70	34.60	35.64	13.88	6.46	
North Texas	2,255,500	23,543,267	197,500	400,500	510,980	633,190	2,786,230	24,576,957	8.8
District, per cent.		95.79		1.63		2.58		100.0	
State, per cent	71.92	45.56	24.92	2.42	26.95	9.17	54.43	32.73	
Texas	3,136,354	51,680,122	792,476	16,515,224	1,896,249	6,900,482	5,118,858	75,095,828	14.7
State, per cent		68.82		21 99		9.19		100.00	
1945 production		1,803,465		692,200		425,264		2,920,929	
State, per cent		61.74		23.70		14.65		100.00	
Ratio production to reserve		28.66		23.86		16.23		25.71	

found per acre for each district. The Gulf Coast, with an average of 60.3 million cu ft per acre, has twice the volume of the next best district, Southwest Texas. The East Texas district will yield an average of only 20 million cu ft per acre, and West Texas an average of about 10 million cu ft. The State average is 20 million cu ft per acre. The associated gas discovered averages 27.3 million cu ft per acre as against the non-associated average of 21.7 million cu ft, and the dissolved gas average of 6.8 million cu ft. This would indicate rather large gas caps. The greatest average discovery per acre by categories is an average of 65 million cu ft per acre of none-associated gas in the Gulf Coast district. On a Btu equivalent of 6000 cu ft per bbl, this is equal to about 11,000 bbl per acre.

● **Natural gas reserves by districts.** Table 3 shows the natural gas reserves for the state of Texas by districts as of January 1, 1946. The total reserve is 75 trillion cu ft or equivalent to 12.5 billion bbl of oil on a Btu basis, of which 24.6 trillion cu ft or 33 per cent is in North Texas, 21.6 trillion cu ft or 29 per cent in the Gulf Coast district, and 15 trillion cu ft or 20 per cent in Southwest Texas. On a Btu basis, therefore, Texas' gas reserve represents about the same number of barrels as the oil reserve.

North Texas, including the Panhandle, accounts for about 46 per cent of the state's non-associated gas reserves. The Gulf Coast is second with 22 per cent and Southwest Texas is third with 19 per cent. This totals 87 per cent, with the rest in the other two districts. The associated gas reserves are located principally in two districts, the Gulf Coast and Southwest Texas, with 53 and 24 per cent, respectively. The dissolved gas reserves are principally in West Texas, Gulf Coast, and East Texas districts, with 36, 21, and 19 per cent, respectively.

Although the North Texas-Panhandle area contains 33 per cent of the total gas reserve of the state, it has 54 per cent of the proved surface area, indicating a comparatively low average yield per acre. The 2.8 million acres have an average reserve of only about 8.8 million cu ft as compared to the average of 14.7 million for the State and 53.7 million for the Gulf Coast.

The production of natural gas for the year 1945 in the State of Texas was 2.9 trillion cu ft, which is a ratio of 26:1 on the state's reserve as compared to the oil ratio of about 16:1 reflected by the dissolved gas production ratio. This gas production ratio is on a gross basis without considering the cycled and repressured gas. On a net basis, the ratio is about 30:1.

The non-associated gas production is about 62 per cent of the total, and the associated gas is 24 per cent, with the dissolved gas 14 per cent. If the Btu equivalent of 6000 cu ft to a barrel of oil is used, the production of equivalent barrels would be about 1,600,000 bbl a day.

● **Natural gas liquids reserves by districts.** Table 4 shows the natural gas liquids of pentane plus contained in the gas reserve figures shown on Table 3. In fields where cycling or natural gasoline plants are available and capable of extracting propane and butane, these liquids are included in the estimates. Almost all of the liquids reserves have been estimated on the basis of actual yields rather than calculated yields.

The reserve of natural gas liquids in Texas as of the first of January, 1946, was 1.5 billion bbl, which is equivalent to about 12.5 per cent of the oil reserves of the state. These reserves were divided 52 per cent in non-associated gas, 21 per cent in associated gas, and 27 per cent in dissolved gas. The important difference in percentage between the gas reserve and natural gas liquids reserve is in the dissolved gas, which has only 9 per cent of the gas reserve but 29 per cent of the liquids reserve. This is due to the higher yield from the dissolved gas. The dissolved gas has an average yield of 59 bbl per million cu ft as compared 15 bbl for the non-associated gas, and 19 bbl for the associated gas. The State average is 20 bbl. The Gulf Coast has the greatest percentage of the natural gas liquids reserve with 30 per cent. North Texas is second with 23 per cent and East Texas is a close third with 22 per cent.

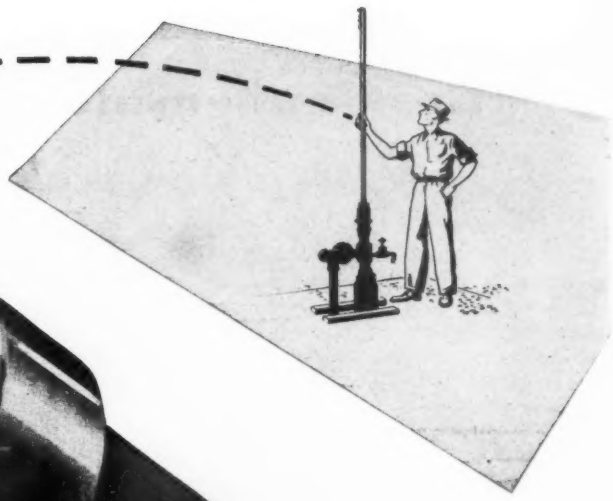
The reserve of natural gas liquids per acre is largest in the Texas Gulf Coast. This district has a reserve of 1142 bbl per acre, whereas East Texas and Southwest Texas have 580 bbl and 326 bbl per acre, respectively. The average for the state is 294 bbl per acre. This does not include the possible conversion of the lighter gases into liquids.

● **Natural gas liquids production.** The 1945 production of natural gas liquids in Texas was 61.5 million bbl or about 168,000 bbl per day. The ratio of liquids production to reserve is 24:1 and represents about 8 per cent of the total oil production. ★ ★ ★

TABLE 4. State of Texas natural gas liquids reserves as of January 1, 1946, by districts.

Thousands of barrels

	Non-associated reserve		Associated reserve		Dissolved reserve		Total reserve		Avg. yield per MMCF, bbl
	Total	Per acre	Total	Per acre	Total	Per acre	Total	Per acre	
Gulf Coast	238.647	1.307	183,632	1.005	35,622	0.184	457,901	1.142	21.2
District, per cent	52.12		40.10		7.78		100.00		
State, per cent	30.58		58.39		8.73		30.47		
East Texas	107,460	0.317	24,363	0.329	205,583	0.872	337,406	0.580	37.0
District, per cent	31.85		7.22		60.93		100.00		
State, per cent	13.77		7.75		50.40		22.45		
Southwest Texas	139,562	0.434	43,772	0.257	24,861	0.083	208,195	0.326	13.9
District, per cent	67.03		21.03		11.94		100.00		
State, per cent	17.88		13.92		6.10		13.86		
West Texas	433	0.011	50,778	0.303	107,250	1.63	158,461	0.223	32.6
District, per cent	.27		32.05		67.68		100.00		
State, per cent	.06		16.15		26.30		10.54		
North Texas	294,292	0.130	11,925	0.060	34,545	0.068	340,762	0.122	13.9
District, per cent	86.36		3.50		10.14		100.00		
State, per cent	37.71		3.79		8.47		22.68		
Texas	780,394	0.249	314,470	0.397	407,861	0.215	1,502,725	0.294	20.0
State, per cent	51.93		20.93		27.14		100.00		
1945 production	33,326		10,282		17,952		61,560		
State, per cent	54.14		16.70		29.16		100.00		
Ratio production to reserve	23.42		30.42		22.72		24.41		
Total oil production, per cent	4.43		1.37		2.39		8.19		



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Gas-condensate reservoirs--a review*

By O. F. THORNTON, The Texas Company

● **Abstract.** Ten years of operation of gas-condensate reservoirs has verified the necessity for and practicability of cooperative and unitized operation. The operating method for each reservoir should be based upon the characteristics of the gas condensate at reservoir conditions. Other factors such as richness of the gas, size of the reserve, capacities of wells, nature of the reservoir, and mode of occurrence of the gas condensate must be considered. Marketing conditions and other economic factors also are important. Due to the increasing volume of the gas market, and prospects for chemical conversion of gas to liquid fuel by the Fischer-Tropsch process, many operators will be required to make a choice or compromise between complete pressure maintenance and gas sales. This can be done intelligently with known methods of evaluation.

● **Introduction.** Gas-condensate fields (also called gas-distillate) are today quite commonplace on the Louisiana and Texas Gulf Coast, but are not confined to that area. The frequency with which they are being discovered and their economic importance in the petroleum industry have increased tremendously with the trend toward deeper drilling. A common understanding of best operating practices by oil operators, land or royalty owners, regulatory bodies, and legislators is necessary if all parties of interest are to cooperate in realizing the maximum potentialities from these fields.

During the past decade in particular, much has been learned and written regarding each of the many phases of gas-condensate operations. It is the purpose of this paper to review the accepted practices, so that the modern basic thought may be available in summary form.

For the purpose of this review, all underground sources of supply from which condensate can be produced are called gas-condensate reservoirs. The name is prefixed with "gas" to emphasize the fact that the condensate is associated with gas when produced. The methods used to evaluate gas-condensate reservoirs, and the basic principles governing the selection of the best method of operation for a particular reservoir, are outlined in the paragraphs that follow.

● **What is condensate?** The terms used in discussing gas condensates have not crystallized as yet into a standard nomenclature. For instance, both distillate and condensate are used synonymously to describe the liquid produced in the tanks. It has been necessary herein to adopt somewhat arbitrarily a set of terms, and to explain the meaning of each term as introduced to avoid confusion.

All are more or less familiar with the fact that some wells produce, together with large volumes of gas, a water-white or light straw-colored liquid that resembles gasoline or kerosine in appearance. This liquid has been called "distillate" because of its resemblance to products obtained in the refinery by distilling the volatile components from crude oil. Also it has been called "condensate" because it is condensed out of the gas produced by the well. The latter term shall be used throughout this paper.

Condensate normally differs markedly from conventional "crude oil." The color of crude oil is usually dark green or black; it feels oily when rubbed between the fingers; it contains some gasoline, but usually is made up in larger part of dark-colored, "heavy" non-volatile components; its API gravity, which is a measure of its weight or density, is commonly less than 45 deg. On the other hand, condensate is light-colored; it evaporates rather easily as compared with crude oil; it contains a large percentage fraction of gasoline and other volatile petroleum components; its API gravity usually is above 50 deg.

Table 1 is a comparison of a typical condensate with a crude oil, which brings out the differences discussed previously herein. Also shown is the amount of gas produced with each, expressed as cubic feet of gas per barrel of liquid. The gas-to-liquid ratios of wells producing gas condensate usually range from 10,000 cu ft to more than 100,000 cu ft per bbl. Gas is produced with crude oil usually in ratios of 100 to over 1000 cu ft per bbl, or much less than with gas condensates.

These limitations of gas-liquid ratios, gravity, and color do not serve to differentiate crude oil and condensate in all cases. Condensates with gravities as low as 40 deg. API have been discovered, and some condensates are produced with gas in low ratios below 10,000 cu ft per bbl.

Now the most important property of condensate from the standpoint of operation of gas-condensate fields is this: The condensate can be "dissolved" entirely in the gas with which it is produced if the temperature is sufficiently high and if there is enough gas present. This is the reverse statement of the familiar phenomenon that a liquid can be condensed out by cooling or chilling many gases.

The temperatures in underground reservoirs containing gas condensate range from 100 to more than 250 F, as measured by thermometers lowered to the bottoms of wells. Similarly, pressures measured with recording gages lowered into the wells are from 1000 psi to over 6000 psi. These conditions are favorable for the gas-condensate mixture to be completely in the gaseous state in the reservoir.

● **Composition of gas condensate.** Knowledge of the gas-liquid ratio and the gravity of the liquid is not sufficient to describe the composition of gas condensate for all purposes. Both the ratio and gravity of condensate depend upon the temperature and pressure at which the separation is made. Therefore, it is customary to express composition in terms of the percentage of each hydrocarbon in the gas, in the condensate, and in the gas-condensate mixture. These percentages are obtained by analyzing the gas and condensate produced, or by analysis of a sample taken at the bottom of a well.

The gas produced from most gas-condensate reservoirs is predominantly methane and ethane with smaller amounts of propane, butane, pentanes, hexanes, and heptanes and heavier, decreasing in that order. The condensate is predominantly heptanes and heavier, with decreasing amounts of hexanes, pentanes, and butanes, and smaller amounts of propane, ethane, and methane. The percentage composition of both the gas and condensate portions of a typical gas condensate are shown in Table 2. Also, the analysis of the gas condensate as it existed in the reservoir is given. These analyses are compared with those of a crude-oil-gas mixture.

The main differences between the gas condensate and the crude-oil-gas mixture noted from Table 2 are: (1) the

TABLE 1. Comparison of condensate and crude oil.

	White gasoline	Gulf Coast condensate	Crude oil
Gravity, °API	59	54.7	38.6
Color	Water-white	Light-straw	Dark-green
Gasoline, per cent	100	70	31
Kerosine, per cent	..	16	16
Heavier than kerosine, per cent	..	14	53
Cubic feet of gas per bbl of liquid	Distilled from a crude oil	18,200	900

*Prior to revision as given herein this paper was presented before the annual meeting of the American Petroleum Institute, Chicago, Illinois, November 12, 1946.

* Pittsburgh
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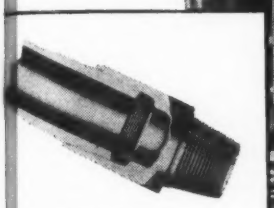

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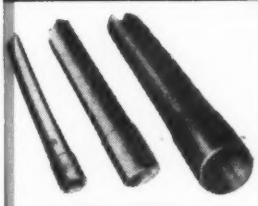
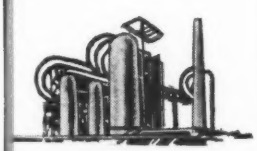


OIL WELL CASING AND TUBING



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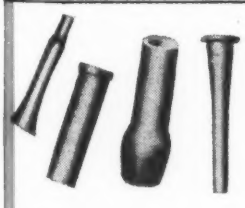

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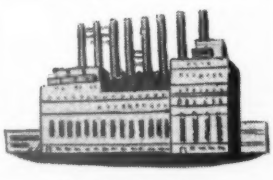

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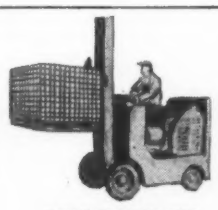

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TABLE 2. Compositions of a gas-condensate and a crude-oil-gas mixture.
(All figures in mole per cent)

	Gas-condensate			Crude-oil-gas mixture		
	Gas	Condensate	Reservoir fluid	Gas	Oil	Fluid reservoir
Methane	91.32	..	87.07	92.80	..	57.83
Ethane	4.43	..	4.39	3.79	..	2.75
Propane	2.12	1.41	2.29	1.97	1.61	1.93
Butanes	1.36	5.71	1.74	0.96	2.24	1.60
Pentanes	0.42	8.11	0.83	0.28	2.45	1.15
Hexanes	0.15	10.46	0.60	0.13	3.47	1.59
Heptanes and heavier	0.20	74.31	3.08	0.07	90.23	33.15
Total	100.00	100.00	100.00	100.00	100.00	100.00
API gravity of heptanes and heavier, deg.		51.2			36.9	
Molecular weight of heptanes and heavier		157			226	

gas condensate contains relatively large amounts of methane and ethane, which are gases; (2) an appreciable portion of the liquid condensate is composed of propane, butanes, and pentanes, whereas the crude oil is predominantly "heptanes and heavier"; (3) the characteristics of the heptanes and heavier in the condensate and in the crude oil are quite different. That of the crude oil is much heavier, as denoted by its low API gravity and its high molecular weight.

Propane, butanes, and pentanes are hydrocarbons that can be recovered and sold as liquids if the gas is processed through a plant, but which are not recovered efficiently by conventional separator operation. For this reason, it is usually desirable to consider recovery processes that are more efficient than ordinary low pressure separators when operating gas-condensate reservoirs, in order to extract these hydrocarbons as liquids.

● **Wet gases.** The most familiar gas-condensate reservoirs are of what here will be called the "wet gas" type. This name is adopted merely as a convenience to distinguish them from the other types of reservoirs discussed. Examples of wet gas reservoirs are the Richland field of northern Louisiana and some of the Appalachian gas fields of the East. Very few of the recently discovered gas-condensate fields of the Gulf Coast are of this classification.

Gas produced from a wet-gas reservoir by a well can be passed through a separator operating at a temperature close to that of the atmosphere and a pressure of approximately 500 psi, and a condensate can be recovered. The liquid may be so small in amount that separators are not required; instead the liquid collects in "drips" installed in the flow line, and periodically is blown out. In some cases the quantity of liquefiable hydrocarbons is large enough to justify an extraction plant.

As the gas is produced, pressure in the reservoir drops at a rate dependent on the rate of gas production and the producing capacities of the wells decline. The amount of liquid recoverable from each thousand cubic feet of produced gas, however, remains constant throughout the producing life of a field containing wet gas. The field is abandoned when the pressure in the reservoir has dropped to such a low value (usually less than 500 psi) that the volume of gas and condensate that can be sold from each well is not sufficient to pay operating expenses. In some cases water encroaches into the reservoir and, therefore, the pressure is maintained at a high level. In this event, the field is abandoned when water has flooded out all the wells.

In Fig. 1 are shown typical performance characteristics of a hypothetical wet gas reservoir. The decrease in reservoir pressure, and the constancy of the yield of condensate, will be noted. The distinguishing feature of wet type gas-condensate reservoirs is this: The amount of recoverable liquid that is contained in each thousand cubic feet (often abbreviated MCF) of the gas produced by the wells remains the same at all times. The percentage of the condensate and liquefied hydrocarbons ultimately recovered from the reservoir, therefore, is equivalent to the percentage of the gas recovered, usually 80 to 90 per cent.

It is possible to obtain a sample of the gas-condensate mixture as it exists in the reservoir by lowering a special container down into a well. By a suitable remotely controlled valve arrangement, the sample can be sealed in the container at the bottom of the well, so that the gas condensate does not escape when the "bottom-hole sample" is brought to the surface. Such a sample can then be taken into the laboratory and placed in a bath of the same temperature as that at the bottom of the well. By this means, the condition of the gas-condensate mixture as it existed in the reservoir can be observed. It is found that, in the case of wet gas reservoirs, the gas condensate is completely in the gaseous state at reservoir conditions.

Removal of gas from the reservoir can be duplicated in the laboratory by opening a valve on the sample container and bleeding off the gas[1]. In the laboratory, as in the field, it is observed that the amount of condensate recoverable by cooling the "produced" gas to the temperature of the atmosphere in a separator remains constant at all times. No liquid drops out in the sample container, however, so long as the temperature is maintained at that of the reservoir. In this respect, the wet gas type differs from a second class of gas-condensate reservoirs, which will be discussed hereinafter.

● **Retrograde type gases.** Typical and well advertised examples of the second type of gas-condensate reservoir are the Big Lake field, Reagan County, Texas[2] and the La Blanca field, Hidalgo County, Texas[3]. Here, as in the case of the wet gas class discussed hereinbefore, a liquid condensate was recovered upon passing the gas produced by the wells through separators operating at atmospheric temperature. As the gas was produced, pressure in the reservoir dropped. However, in these cases it was observed that, as the pressure dropped, the yield of condensate from each thousand cubic feet of gas declined. In this latter respect it differed from the wet gas type. Fig. 2 shows how the condensate in gas from 19 wells in the La Blanca field[3] declined from 31 bbl of liquid (pentane and heavier) per million cubic feet of gas (often abbreviated MMCF) down to 22 bbl per million in three years—a reduction of 29 per cent. Obviously, a considerable portion of the condensate remained in the reservoir and was not produced. The loss of this condensate was of sufficient magnitude to be of economic importance.

Again, an explanation of the observation made in the field can be obtained in the laboratory. A bottom-hole sample from a La Blanca well[4] was placed in a bath at reservoir temperature as previously described. The material was found to be entirely in the gaseous state. However, when removal of gas from the reservoir was simulated by dropping the pressure in the sample container held at reservoir temperature, it was observed that a liquid was condensed within the container.

A logical explanation of what happens in the field is apparent. When the pressure is dropped, due to withdrawal of gas, a liquid condenses in the reservoir. This liquid, composed largely of condensate otherwise recoverable at the surface, "wets the sand" and, therefore, will not normally be produced by the wells.

This type of condensation, which is attributable to a drop in pressure while the temperature of the gas remains constant, is called "retrograde condensation." Similarly, the gas condensates, from which such condensation is observed at reservoir temperatures, are called herein "retrograde gases." Most of the gas-condensate reservoirs contain gases of this type.

It has been observed in laboratory tests that the amount of liquid which drops out by retrograde condensation is higher for rich gases, i.e., those from which large condensate yields are obtained. It has been estimated[5, 1] that approximately 50 per cent of the recoverable liquid content of some gas condensates would be lost by retrograde condensation in the formation if the reservoir were produced and the pressure allowed to decline. In the case of "lean" retrograde gases, the loss would be less. The laboratory evaluation of the amount of possible retrograde loss, using bottom-hole samples made by combining surface gas and liquid, has been described in the literature[1].

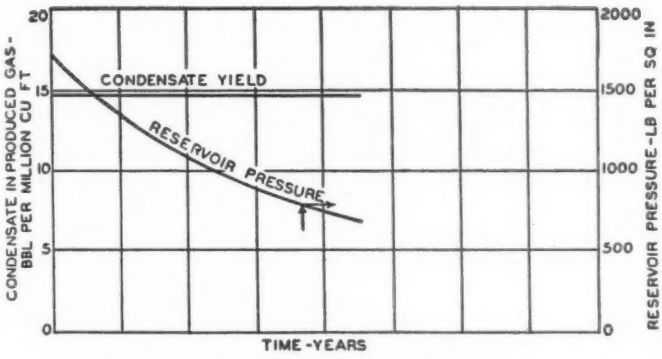

FIG. 1. Performance characteristics of reservoir producing "wet"-type gas.

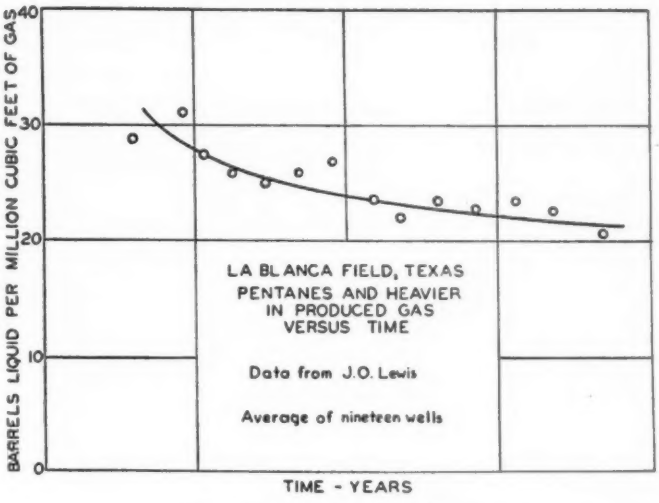

FIG. 2. Decline in condensate yield from a retrograde-type gas.

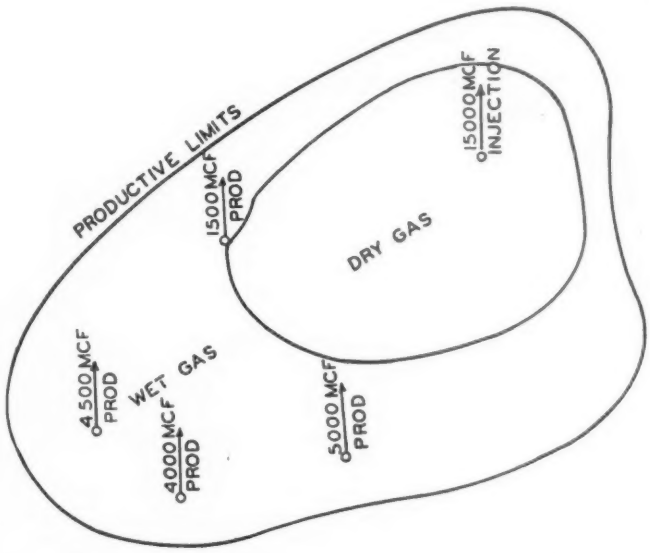

FIG. 3. Location of wells in typical cycling plan.

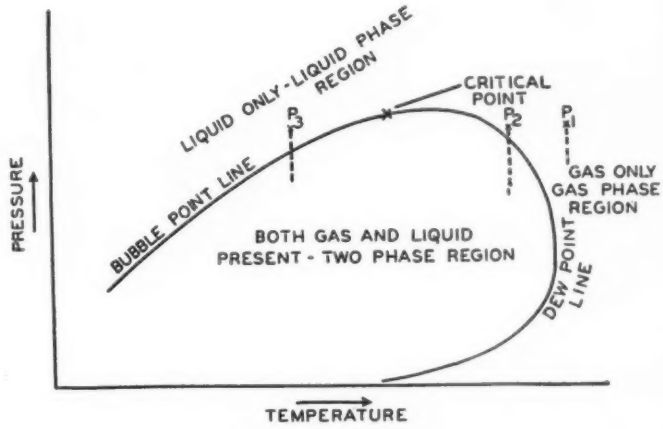

FIG. 4. A phase diagram.

In order to reduce the loss due to retrograde condensation, the process called cycling (or recycling) has been developed. By this operation, gas condensate is produced from strategically located wells, the liquefiable hydrocarbons are removed, and the stripped gas, instead of being sold, is compressed and returned to the same reservoir from which it was produced through injection wells. These injection wells are also located strategically, and some distance from the producers. By injection of residue gas, pressure drop in the reservoir is prevented and, therefore, retrograde condensation is held to a minimum. Eventually, the injected "dry" gas displaces most of the "wet" gas between the injection and producing wells. These latter wells then begin to produce some of the dry gas, and the amount of wet gas produced begins to decrease. When the amount of dry gas becomes so large that the liquefiable hydrocarbons recovered from the small volume of wet gas will not pay operating expenses, the cycling process is abandoned. The gas in the field then can be sold, and reservoir pressure allowed to decline as in the case of the wet-gas type. It is estimated[6, 7] that between 60 and 80 per cent of the condensate in a reservoir can be obtained by cycling. If cycling is followed by gas sales, the recovery may, of course, be increased—possibly to 80 to 90 per cent.

A map (Fig. 3) shows a typical arrangement of wells in a cycling project, with daily volumes produced and injected per well. Also the area occupied by dry gas at a particular time is designated to illustrate the mechanism of displacement of the gas.

The area shown in Fig. 3 as being occupied by dry gas was determined by what is called a "model study" of the reservoir[8]. It can be shown that the flow of gas in a reservoir follows the same pattern as the flow of electricity in a conductive "model" of the field. These models are built to scale, and current is put in at points corresponding to injection-well locations, and current is taken out at producing wells. The amount of current per well is made proportional to the volume of gas produced by, or injected into, the well. By actual experience, it has been found that the dry-gas patterns determined by model study agree reasonably well with those obtained by observing dry gas encroachment into producing wells. Of course, the dimensions of and conditions in the reservoir must be accurately known, so that the model is an accurate picture of actual subsurface conditions. The use of electric models as guides by operators of cycling projects now is widespread.

● **Relation of types.** In discussing each of the gas condensates, viz., the wet gas and retrograde gas types, it was desirable to describe the properties of the gas condensate in the laboratory under reservoir conditions of temperature and pressure. In order to point out the similarity between the types, once again laboratory tests will be resorted to.

Assume that another bottom-hole sample of gas condensate is obtained. In the laboratory, it is observed to be entirely in a gaseous state at reservoir temperature and pressure. Now, instead of reducing pressure in the container by bleeding off gas, let the pressure drop be accompanied by expanding the size of the container. This may be done by a movable piston in one end of the container. Further, inasmuch as conditions can be varied at will in the laboratory, observations can be made at any desired temperature in addition to that of the reservoir. Therefore, the characteristics of the gas condensate can be observed

at a great many combinations of pressure and temperature.

The results of a number of such observations for a given gas condensate can be summarized as follows: At high temperatures, the mixture is entirely in the gaseous state or phase, and it remains gaseous at all pressures. This condition corresponds to the wet-type gas. At slightly lower temperatures, the mixture is in the gas phase at high pressures, but, when the pressure is reduced, a liquid phase condenses. This corresponds to the retrograde type gas. Therefore, it is seen that the particular type of classification into which a gas condensate falls depends not only on the amount of gas in the gas condensate as discussed hereinbefore, but also on the temperature and pressure of the reservoir. The same gas-condensate mixture can be classed as either of the two types, dependent on conditions.

Fig. 4 is a picture of the previously given word summary, called a "phase diagram." There are three regions on this diagram: in one, the pressure and temperature are such that only a gas phase is present; at slightly lower temperatures and at intermediate pressures, both gas and liquid phases are present, i.e., a two-phase region; at lower temperatures and high pressures, only a liquid phase is present.

Assume that reservoir conditions of temperature and pressure correspond to the point P_1 in the diagram. The mixture is entirely in the gas phase. If, at the constant reservoir temperature, the pressure were dropped (as by production of gas from the reservoir), the corresponding path on the phase diagram would be a vertical line from P_1. It will be noted that such a line does not enter the two-phase region; the mixture remains entirely a gas, or behaves as a wet gas.

If pressure-temperature conditions of the reservoir were equivalent to those designated by P_2, the mixture would be in a gaseous state. If, at the constant reservoir temperature, the pressure were dropped (as in the La Blanca field), a liquid would condense. This is shown in the phase diagram by the vertical line crossing into the two-phase region. Consequently, the mixture would be classed as a retrograde gas. The pressures at which the liquid first began to condense is called the "retrograde dew point." If the pressure were dropped to a very low value (an extension of the vertical line from P_2), the region wherein a gas phase only is present again would be entered. This means that the liquid that condensed as described would revaporize if the pressure were reduced to a very low value.

In a similar manner, it will be noted that if the reservoir fluid is at a reservoir temperature and pressure corresponding to P_3, it is entirely in a liquid phase. A drop in pressure causes a gas to be liberated (two-phase region). The pressure at which a gas first forms is called the "bubble point."

It was stated previously herein that at certain conditions the reservoir fluid was entirely in a gas phase, whereas at others it was wholly a liquid. The question may be asked: "How is it determined that the mixture is a gas and not a liquid?"

At extremely high pressure of the reservoir, many familiar concepts of "liquids" and gases" no longer apply. For instance, at 6000 psi gases are compressed to about one-four hundredth of their volume at atmospheric pressure. A cubic foot of gas is reduced in volume to less than a 2-in. cube. At these high pressures, therefore, gases begin to react much like liquids. Conversely, when as much as 2000 to 5000 cu ft of gas is mixed with a barrel of liquid (about 5 cu ft), the mixture begins to react much like a gas at high pressure.

As a matter of fact, there is one condition of temperature and pressure for each gas condensate, called the "critical point" (Fig. 4), where it is impossible to distinguish whether the gas condensate is a liquid or a gas. As this point is approached, the gas and liquid phases become identical in all characteristics.[7-9]

● **Critical type.** Some gas-condensate reservoirs have been discovered in which conditions are very close to the critical. As a rule, the gas to liquid ratio in such cases is below 10,000 cu ft per bbl.

Laboratory evaluation of this "critical" type of gas-condensate is difficult, and often it is impossible by direct observation to distinguish whether the gas-

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. . . 2 *The usual flush design with no shoulders for stopping a slipping drill collar.*

. . . 3 *The drill collar's hard heat-treated surface that reduces gripping efficiency.*

and 4 *The relatively low drill string weight available for wedging the slips into the bowl.*

That's why safety-minded operators throughout the world have adopted Baash-Ross Drill Collar Slips as "must have" rig equipment, because these Slips are *specially designed* to overcome the risks of supporting a drill string in the rotary table. In contrast to the normal fixed-curvature design of rotary slips, the unique multi-segment design of Baash-Ross Drill Collar Slips permits them to w-r-a-p around the drill collar like a chain tong. They take a full slip-proof grip whether the drill collar is new or worn, round or out-of-round. *And they automatically compensate for as much as 1½" change in drill collar diameter — more than ample for modern drilling operations.*

For example, note in the table how a Baash-Ross Drill Collar Slip that fits a 7" diameter drill collar will also fit *any* diameter down to 5½". Adjustment for wear is automatic and continuous throughout the working range!

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Sizes and Operating Ranges of Baash-Ross Drill Collar Slips

SIZE*	Operating Range	
	From	To
A	3"	4½"
B	3¾"	5¼"
C	4¼"	5¾"
D	5½"	7"
E	6¾"	8¼"

*(all sizes available in both "Regular" and "Long" types)

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Baash-Ross Drill Collar Slips are available in two types —"Regular" and "Long." The "Long" type has extensions above the gripping area to provide a seat for the Baash-Ross Safety Clamp — the clamp that puts a non-slip, *yet removable*, "stop shoulder" on *any* drill collar to compensate for the hazards of flush design when supporting the collar in the table. For complete details see your nearest Baash-Ross representative — or write direct!

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ORDINARY SLIPS that fit the drill collar when new (A) are unable to adjust themselves to smaller diameters as the drill collar wears away. Result, grip becomes less and less adequate (B) and risk of a costly fishing job constantly greater.

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condensate is a gas or a liquid at reservoir conditions.

Where it can be established that the mixture is a liquid at reservoir conditions, it may be argued that such a material is truly a crude oil and that operation of the reservoir should be the same as for a conventional oil reservoir. However, the losses that could result from such practices should be pointed out.

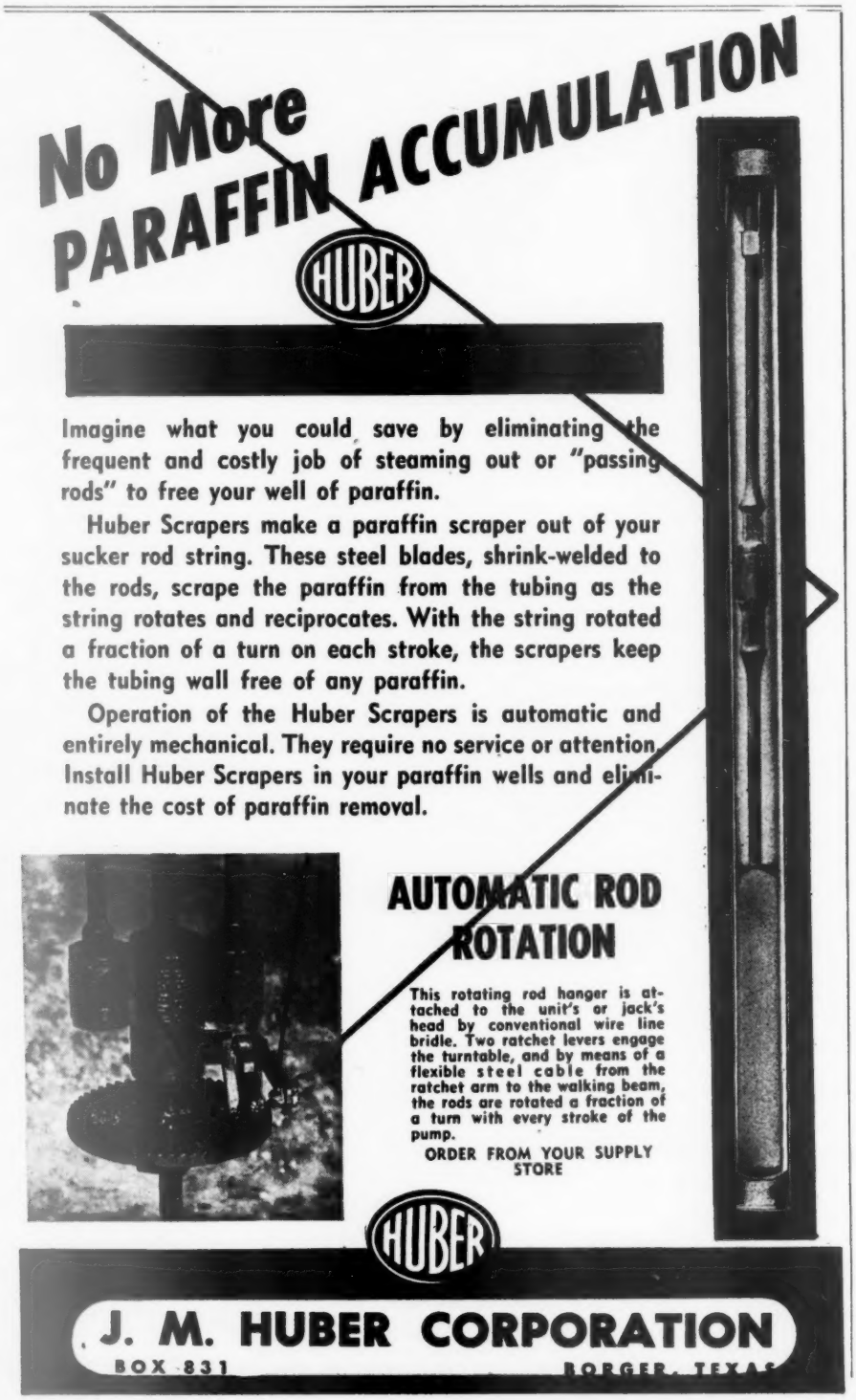
The liquid produced from these reservoirs is similar to that described for typical gas-condensate reservoirs. It is light straw in color and has a high API gravity. It contains a large amount of light hydrocarbons. If more gas is mixed with the liquid than was produced with it—say on the order of 10,000 cu ft per bbl

TABLE 3. Comparison of gas condensates with crude-oil-gas mixtures.

	API gravity of liquid, deg	Gas-liquid ratio, cu ft per bbl	Reservoir conditions		Retrograde dew point, psi	Bubble point, psi
			Temperature, °F	Pressure, psi		
Gas condensate:						
Wet gas	65	67,000	160	1,700	..	..
Retrograde gas	55	18,500	203	4,810	4,470	..
Reservoir liquid	58	2,700	203	4,700	..	3,855
Crude-oil-gas mixture:						
Mid Continent	38	540	98	1,760	..	1,700
Gulf Coast	38	900	211	4,750	..	4,600

TABLE 4. Comparison of extraction methods.

	Conventional separation	Multi-stage separation	Plant Extraction
1. Barrels of liquid per million cubic feet of retrograde gas	52	58	70
2. API gravity of recovered liquid, deg	54.7	58.4	64.4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—it can be observed in the laboratory that the mixture is entirely in a gaseous state at reservoir conditions of temperature and pressure. The liquid therefore has all the attributes of typical condensate; however, the amount of gas present with it is insufficient to "dissolve" it at reservoir conditions.

The losses by the conventional crude oil operating practices applied to this type of reservoir will be great. First, the loss of butanes, pentanes and other light hydrocarbons due to conventional separator operation amounts to 10 to 25 per cent or more of the liquid recoverable by plant processing. Second, the recovery by any operation whereby the reservoir pressure is not maintained will be very low—from 10 to 25 per cent of the amount originally in the reservoir. If pressure is maintained by gas injection, by water injection, or by restricting production to take advantage of a natural water drive, the recovery can be increased to 40 to 70 per cent or higher.

Table 3 gives data for several gas-condensates and crude oils to illustrate the types previously discussed herein.

● **Occurrence with oil reservoirs.** Wet and retrograde gases often occur as gas caps to crude oil reservoirs. The amount of oil present in such reservoirs has been found to vary considerably. It may be present only as a thin rim of liquid around the flanks of the structure, and may have no commercial significance—or oil may occupy in excess of 90 per cent of the pore space in the reservoir. The relative amounts of oil and gas condensate in such reservoirs have an important bearing upon the operating methods used, and upon the timing of recovery of the two reservoir fluids. In general, the practice has been to give primary consideration to recovery of oil, and recovery from the gas-condensate zone has often been deferred until exploitation of the oil zone was completed. If ownerships of the oil and gas condensate are diversified, some inequity of income at times may result in such cases.

More often than not several gas-condensate reservoirs are found in the same field. The integration of the simultaneous operation of two or more such reservoirs calls for ingenuity in well-completion practices and timing of recovery.

● **Operating methods.** The classification of gas condensates, their properties,

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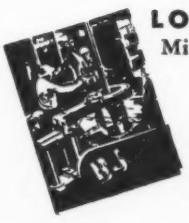

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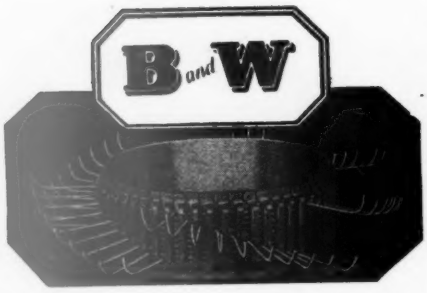

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and modes of occurrence have been discussed previously herein. The operating methods usually applicable to each type have been generally reviewed. There are, however, many exceptions to the general statements made previously. The selection of a particular operating method for a given field should depend upon certain basic principles that are well known to industry.

The basic principles governing best operating methods for gas-condensate reservoirs are not unique and, according to modern thought, are the same as for most oil reservoirs.[6] However, physical waste due to improper operation is both more serious and more easily discernible in the gas-condensate reservoirs and, therefore, the application of these basic principles has been more the rule than the exception. These principles are: (1) Selection of operating methods based upon the character of the reservoir fluids; (2) maintenance of pressure in those reservoirs where a decrease would result in loss of recovery underground; (3) efficient handling of produced fluids at the surface to obtain maximum liquid extraction; (4) optimum spacing of wells to obtain highest recovery; and (5) unitization of interests to assure equity to all parties having ownership in the common reservoir, and to enable application of principles (1), (2), (3), and (4).

Gas-condensate operations may be divided into two classes: (1) Those concerned with efficient recovery of gas condensate from the reservoir through the wells, and, (2) those pertaining to extraction of the liquefiable hydrocarbons from the well production. These two classes of operations are in many cases of equal importance. Inefficient extraction can result in losses as great as those due to retrograde condensation, or inefficient recovery.

The "cycling" operation previously described is now widely utilized for recovering retrograde gases. It is not necessary to cycle wet-type gases to prevent loss of condensate underground. Often, however, no market for gas exists, and by the cycling process the condensate can be recovered without awaiting the development of an adequate gas outlet. If the gas is the gas cap of an oil reservoir, cycling may enable the recovery of the condensate simultaneously with the oil. Production of the gas for sale obviously would cause oil to move into the gas zone, and result in significant loss of oil recovery. For these reasons, some wet-type gases may be cycled.

TABLE 5. Operating methods—summary.

Recovery methods	Extraction methods
1. Cycling	a. Separator—conventional
2. Gas sales or storage	b. Separator—multi-stage
3. Pressure maintenance	c. Plant

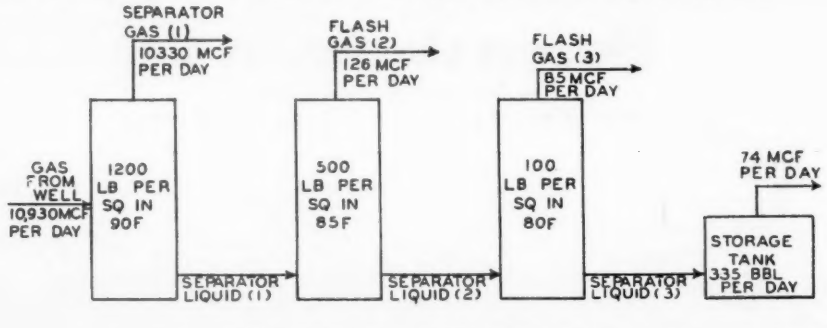
Gas injection to maintain pressure and and prevent retrograde condensation is not necessary if water encroaches into the reservoir as a retrograde gas is produced. In the case of wet gas reservoirs, obviously the pressure need not be maintained, because no condensation takes place in the reservoir as pressure declines. In such cases, when there is a market for gas or when it may be utilized legally for some other purpose, gas-condensate reservoirs may not be cycled. Among other legal methods, in addition to gas sales for which gas has been utilized in such operations, are: injection into an oil reservoir to maintain reservoir pressure and so to increase oil recovery; injection into a gas reservoir of lower pressure for gas storage, and injection into a reservoir containing water for gas storage. The foregoing operating methods and others of similar nature, wherein the pressure in the gas-condensate reservoir is not maintained by residue gas injection, may be called "gas sales or storage" to differentiate them from "cycling."

In the case of critical type reservoirs, maintenance of reservoir pressure is indicated. Injection of gas, injection of water, and restriction of producing rate to take full advantage of natural water drive are commonly applied for "pressure maintenance."

Methods of extracting condensate or other liquefiable hydrocarbons from the well production may be classed as: (1) Separation of gas and condensate in a conventional oil separator operating at approximately atmospheric temperature and a pressure ranging from 100 psi to 500 psi or more; (2) multi-stage separation as described hereinafter, and (3) extraction in a processing plant. These methods are in order of increasing efficiency.

Recovery by a conventional separator is relatively low, ranging from 40 per cent or less to 85 per cent of that obtainable in a plant, depending upon the composition of the gas condensate. By multi-stage separation, recovery efficien-

FIG. 5. Diagrammatic sketch of multi-stage separation of gas-condensate.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FLASH GAS (2)
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FLASH GAS (3)
85 MCF PER DAY
GAS FROM WELL
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500 LB PER SQ IN 85F
100 LB PER SQ IN 80F
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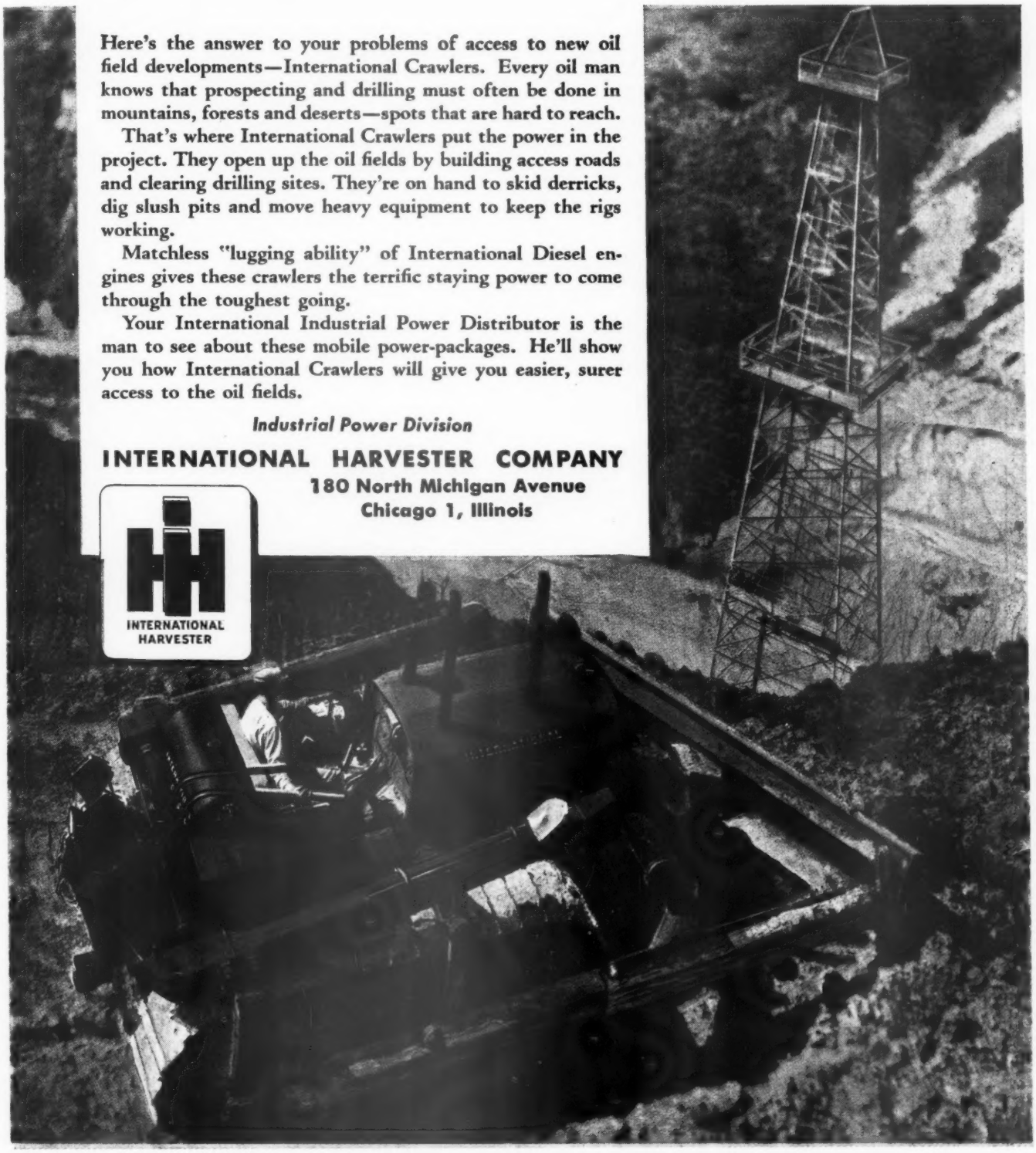

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cy may be increased over that obtainable by use of one separator. Multi-stage separation (or simply stage separation) is illustrated diagrammatically in Fig. 5. Well production enters a separator operating at high pressure, on the order of 1000 psi. The pressure selected usually is the one at which the separator gas retains the least amount of liquefiable hydrocarbons, or the "optimum separator pressure." Liquid from the first separator goes to a second separator at a lower pressure where additional gas is liberated, and so on through additional separators until atmospheric pressure is reached. The temperatures in each of the separators also may be controlled.

Plant processing is most efficient. Many of the plants in operation today of the absorption-oil type recover in excess of 30 per cent of the propane, 80 per cent of the butanes, and substantially all pentanes, hexanes, and heptanes and heavier.

In Table 4 are given the barrels of liquid recoverable by each of the foregoing methods from one million cubic feet of a typical retrograde gas.

Summarizing the foregoing, present operating methods or those utilized in the past for gas-condensate reservoirs are combinations of: (1) cycling; (2) gas sales or storage; or (3) pressure maintenance—with one of the three extraction methods, as indicated in Table 5.

Large-volume gas markets have recently been developed on the Gulf Coast, and the possibility of chemical conversion of gas by the Fischer-Tropsch process into gasoline and other liquid hydrocarbons on a large scale promises to increase substantially gas sales over present volume. More and more operators will be required to make a choice or compromise between cycling with complete maintenance of pressure and gas sales. This it is possible to do intelligently by utilizing the current knowledge concerning gas-condensate reservoirs. Underground losses due to retrograde condensation, and recovery by cycling, can both be estimated with sufficient accuracy as outlined in the previous paragraphs.

The operating method used in a particular case depends upon the evaluation of a number of factors.[10] Obviously, the amount of recoverable liquid in the gas is very important. The cycling and plant processing of gas condensates containing less than 20 bbl to 25 bbl of liquid per million cubic feet usually is not financially attractive, unless there is a market for some of the residue gas from the plant. Also, the size of the reserve must be sufficient to pay out plant and well investments and to yield a reasonable return. Many small reservoirs, containing comparatively rich gas condensates, will not support a processing plant and pay out the cost of installing a compressor plant for cycling without some sale of gas concurrent with cycling.

The capacities of wells are an important factor. Low capacity means a large number of both producing and injection wells must be drilled, resulting in high investment and operating costs.

Subsurface conditions may be so complex as to make cycling unattractive. The presence of numerous complex faults, erratic shale breaks, large variations in permeability, and other nonuniform conditions may make cycling of reservoirs containing lean gases impractical or unprofitable.

Each reservoir presents an individual problem. The operating method selected depends upon the items discussed previously herein, and also upon marketing conditions, and other economic factors. Usually the most important single item in making the selection is whether unitized operation is possible.

● **Unitization.** There is now almost universal agreement that unitization of operating and royalty interests is an essential prerequisite for efficient operation of a gas-condensate reservoir. The primary purpose of unitizing operations is to increase recovery of condensate and other liquefiable hydrocarbons, resulting in increased values to the operator, the royalty owner, and society as a whole. In the foregoing sections of this review, unitization has been tacitly assumed in discussing operating methods.

Results of cycling operations have proved beyond doubt that the reservoir containing gas condensates is itself a unit, with no subsurface lease boundaries. The gas is freely migratory, and the amount of recovery from the reservoir is determined by the *location* of wells—not the number of wells. The *operating* method used is of primary importance, and it should be selected by study of the reservoir as a whole.

In cycling and other pressure-maintenance operations, the objective of efficient operation is to produce the gas condensate, but not to produce the dry gas, water, or other fluid that displaces the gas condensate from the reservoir. This can be done only by locating and operating wells to take advantage of structural position and other conditions in the reservoir. For most efficient operation, lease ownership should not be given any consideration. However, income must be shared by all leases, and not exclusively by those on whose tracts the producing wells are located. Unitization provides a means of equitably sharing the income.

A brief survey of differences between most oil and gas-condensate reservoirs may serve to clarify the more urgent need for unitized operation in the latter type of field. First, dollar recoveries per volume of the reservoir from gas condensate is much less than from oil. For instance, cycling yields on the order of 20 bbl to 200 bbl condensate, and 1,000 MCF to 4,000 MCF of gas per acre-ft, worth approximately $65 to $470 at prices of $1.75 per bbl and $0.03 per MCF, respectively. On the other hand, crude oil yields are on the order of 200 bbl to 1000 bbl per acre-ft, with possible small additional value for gas produced with the oil. Whereas a profit can be made in most cases by drilling an oil well to each 40 acres, the same is not true of gas condensate. Wider spacing of wells means that a well cannot be drilled

* Dimensions of this unit are: Width overall, 33"; Length overall, 114"; Height, 60". Total weight is less than 4,000 pounds.

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on each and every lease and, therefore, units must be formed to prevent gross inequity of income. Second, extraction plants to strip efficiently the liquefiable hydrocarbons from gas condensate require large investments in addition to that for drilling the wells, and it is not often that one operator in a field has sufficient holdings to make the construction and operation of such a plant financially attractive. Third, the actions of one operator in a field affect the operations of all others because of the freely migratory character of gas. This effect is more noticeable in gas-condensate than in oil fields. Thus, one operator by selling gas can (and in some cases has done so) drop the pressure throughout a reservoir containing retrograde gas, resulting in damage to any leases wherein operators are maintaining pressure by gas or water injection.

The foregoing and many other advantages of unitized operation are recognized by all. It is beyond the scope of this review to outline all the arguments[10] for, or the few against, unitization. It is significant that some states require as a matter of law that, in the event a majority of interests in a gas-condensate field desire to unitize to enable more efficient operation, others also must do so. However, almost all the units formed up to now have been voluntary. Operators and royalty owners alike have been assured of an overall income under unitized operation greater than would be obtained by non-unitized operation. This usually can be demonstrated because of the fact that total recovery always is greater by unitized operation.

Even when all parties interested in a given field have agreed that unitization is desirable, the agreement upon a basis for participation in a unit is often difficult. The basic principle for participation in most units has been[6, 12] that each party should share in the unit in the proportion that the recoverable hydrocarbons under his tract, or the value thereof, bears to the total under all tracts. In largely undeveloped fields or those wherein sand conditions are uniform, surface acreage may be an equitable basis of participation. For fields wherein sufficient information is available, the amount of recoverable hydrocarbons can be calculated rather accurately. Net pay thickness, porosity, and water content of the pay are used to calculate the space containing hydrocarbons. The composition of the gas condensate is used to determine what portions of the reservoir fluid are recoverable as liquid and gas. Laboratory tests are made to determine the volume of reservoir space required to hold 1000 cu ft of gas condensate—more commonly called the volume factor. By combining these factors, the amount of gas and condensate under each tract can be computed.

Many of the objections to unitization arise from the fact that the objecting party does not understand the details of the proposed participation formula. Most of the uncertainties and fears which were at first held have now largely disappeared because of many years of successful operation of unitized projects.

Cooperation between operators, royalty owners, and regulatory bodies is essential to efficient operation of a gas-condensate reservoir. Unitization is the mechanism by which this cooperation can be applied to operation of the field.

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10. "Practical Economics of Cycling," B. B. Boatright and P. C. Dixon, *A.P.I. Drilling and Production Practice*, 221-7 (1941).
11. "Unitization—Its Progress and Future," D. R. Knowlton, *A.P.I. Drilling and Production Practice*, 630-34 (1939).
12. API Special Study Committee on Well Spacing and Allocation of Production, *Progress Report on Standards of Allocation of Oil Production Within Pools and Among Pools*, 3 (1942).

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Use of helium as a tracer in oil and gas fields*

By E. M. FROST, JR., *Chemical Engineer*, U. S. Bureau of Mines

I AM pleased to have this opportunity of bringing to your attention the use of helium as a tracer in oil and gas fields. Though the practical development of the use of helium as a tracer started only recently, we have to date engaged in helium tracer projects in three widely separated fields; and in one instance, are carrying on two separate projects simultaneously in the same field. In each project undertaken, we have been able to provide the operators with valuable information that could not be predicted and could not be determined by any other presently known practical means. A project was completed in the Elk Hills, California, field last summer and a report on the work has been published as *Report of Investigation No. 3897*. A project was begun in the Slaughter, Texas, field last December and is complete except for a few final observations. A project was begun in the Cabin Creek, West Virginia, field during the past summer and is progressing successfully. Reports on the last two projects will be published as soon as the data can be assembled.

When used as a tracer gas, small percentages of helium are mixed with natural gas being pumped into a reservoir for conservation, repressuring, or cycling purposes. Minute quantities of helium added to natural gas can be detected by analytical methods and accurately determined. Consequently, when helium-enriched gas displaces or intermingles with natural gas being produced, the variations of the helium content of the produced gas from various parts of a field give interesting and long-sought data on the movement of injected gas through reservoirs.

Some general information about helium itself may be of interest. Helium is one of the basic forms of matter, commonly known as an element, if one discounts the present trend toward splitting of the atoms. It occurs in dilute form in practically all natural gases from the United States, and even in the air we breathe. In most instances, however, it is present in only minute amounts, often a few thousandths or even a few ten-thousandths of a per cent. Few natural gases contain as much as one half of one per cent helium, and a natural gas containing one per cent or more is rare. Thus, helium is not manufactured, but is found to occur naturally.

Helium for military and commercial purposes is extracted from the helium-bearing natural gases, and a tremendous volume of natural gas must be processed to obtain quantity production of helium. Helium is the next lightest gas known, is non-flammable, does not enter into any known chemical reactions, and is the least soluble of any of the presently known gases. Initially its principal use was in balloon service. It is coming into use as an inert agent in metallurgical operations, as a tracer gas in oil and gas fields, and is used diluted with oxygen for the hospital treatment of patients afflicted with lung, chest, and throat ailments. It has played an important part in deep-sea diving and rescue work.

The mechanics of helium tracer work are relatively simple. An intensive survey is made first to determine the initial helium content of the gas from the producing wells and of the gas being injected or to be injected. This survey comprises sampling the wells to be involved each day for several days or possibly for a week, and analyzing the samples for helium content. After this preliminary sur-

*Presented at meeting of the Petroleum Division, American Institute of Mining and Metallurgical Engineers, Galveston, Texas, October 3, 4, and 5, 1945. Much of the material contained in this print has been published by the U. S. Bureau of Mines in Reports of Investigation 3897 and 3899.

FIG. 1.

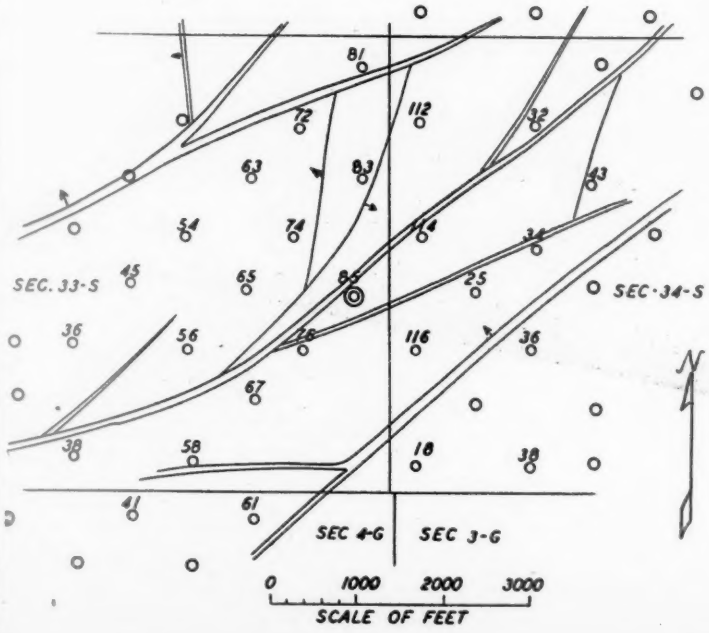
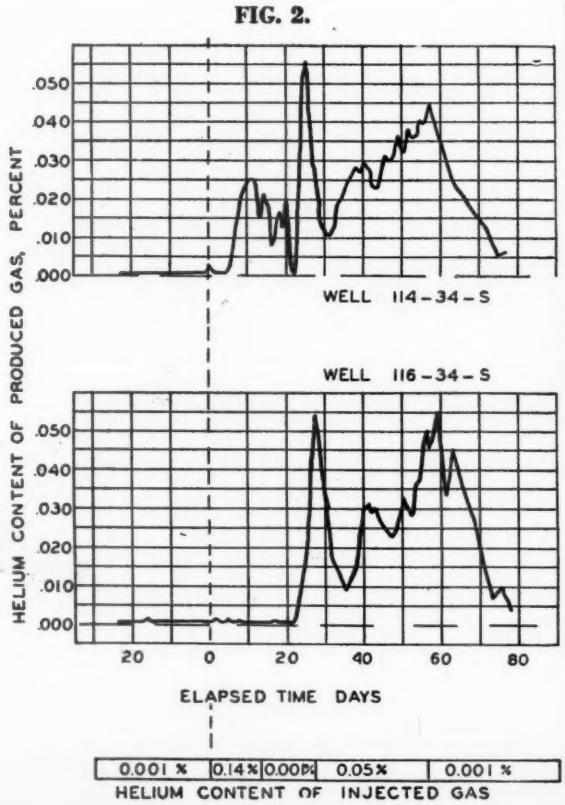
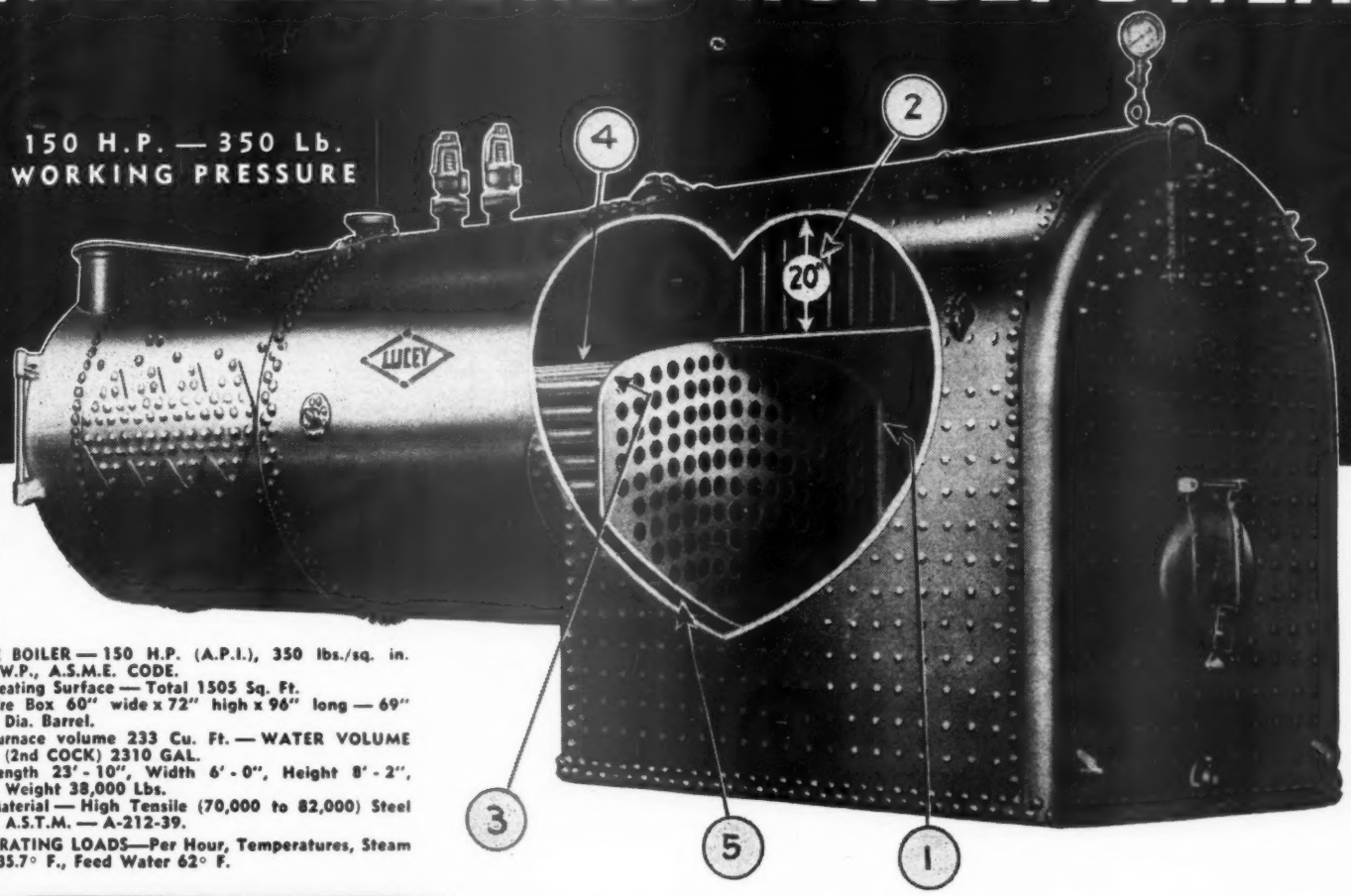


FIG. 2.



THOROUGHBRED HORSEPOWER

150 H.P. — 350 Lb.
WORKING PRESSURE



E BOILER — 150 H.P. (A.P.I.), 350 lbs./sq. in. S.W.P., A.S.M.E. CODE.
Heating Surface — Total 1505 Sq. Ft.
Fire Box 60" wide x 72" high x 96" long — 69" Dia. Barrel.
Furnace volume 233 Cu. Ft. — WATER VOLUME (2nd COCK) 2310 GAL.
Length 23' - 10", Width 6' - 0", Height 8' - 2", Weight 38,000 Lbs.
Material — High Tensile (70,000 to 82,000) Steel A.S.T.M. — A-212-39.
PERATING LOADS—Per Hour, Temperatures, Steam 435.7° F., Feed Water 62° F.

1 WELDED FIRE BOX — Lucey Standard. No laps, no rivets to overheat or burn. Quicker heat-transfer.

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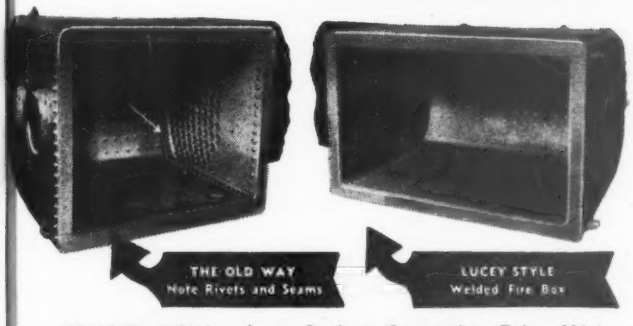

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FIG. 3.

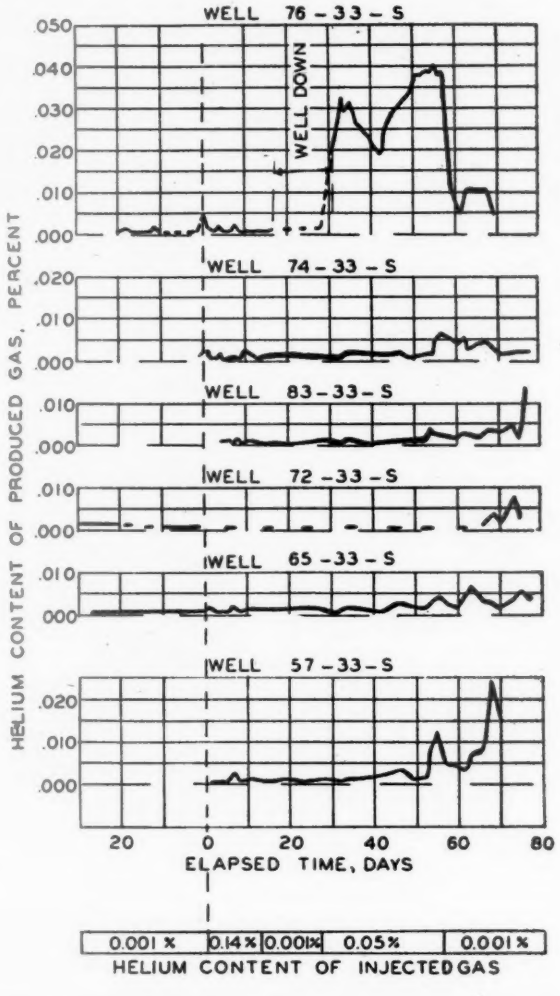
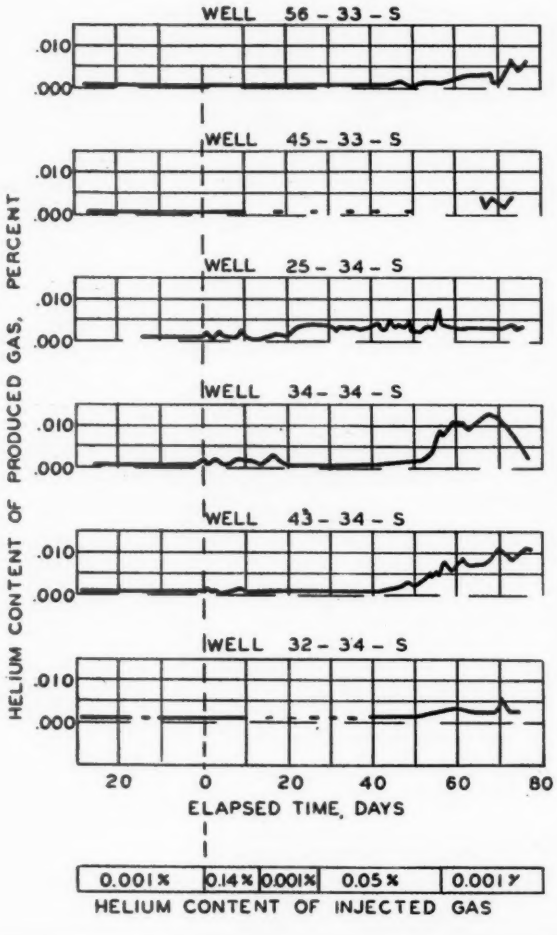

WELL 76 – 33 – S
WELL DOWN
WELL 74 – 33 – S
WELL 83 – 33 – S
WELL 72 – 33 – S
WELL 65 – 33 – S
WELL 57 – 33 – S
HELIUM CONTENT OF PRODUCED GAS, PERCENT
.050
.040
.030
.020
.010
.000
20 0 20 40 60 80
ELAPSED TIME, DAYS
0.001 % 0.14 % 0.001% 0.05 % 0.001 %
HELIUM CONTENT OF INJECTED GAS

FIG. 4.


WELL 56 – 33 – S
WELL 45 – 33 – S
WELL 25 – 34 – S
WELL 34 – 34 – S
WELL 43 – 34 – S
WELL 32 – 34 – S
HELIUM CONTENT OF PRODUCED GAS, PERCENT
.010
.000
20 0 20 40 60 80
ELAPSED TIME, DAYS
0.001 % 0.14 % 0.001% 0.05 % 0.001 %
HELIUM CONTENT OF INJECTED GAS

vey helium is added to the injected gas for a limited period of time and in concentration sufficient to form an easily-perceptible wave of helium-enriched natural gas in the formation. The addition of tracer helium then is discontinued. Gas from the producing wells is analyzed at regular intervals for an extended period of time. Arrival of tracer helium at the producing wells is revealed by the variations in the helium content of the produced gas.

The length of time required for the tracer helium to show at wells offsetting the injection well during the Bureau's work has been unpredictable. In some instances, it has appeared within a few days, whereas in other instances it has not appeared at the end of six months. The results obtained in the tracer work have contradicted without exception the predictions of the operators and in some instances proved conclusively and decisively that some rather deep convictions of the operators were incorrect.

The most satisfactory method of presenting the findings of our tracer work is by means of projection slides. I have prepared a number of these slides, and will discuss them individually. The first group relates to the work done in the Elk Hills field.

● **Fig. 1.** This is a map of that portion of the Elk Hills field in which our helium tracer work was done. The injection well is identified by the double circle near the center of the figure. The double and single lines crossing the map represent fault lines established by electric log correlations, drilling records, and bottom-hole pressure surveys. Many of the faults were presumed by the operators to be barriers to the migration of gas, and in discussions with the operators preceding the tracer work, it was the expressed conviction of several that the injected gas was being confined between the fault lines on either side of the selected injection well.

Approximately 2,000,000 cu ft of natural gas per day was injected into the injection well at a pressure of approximately two hundred pounds. The initial helium content of this injected gas was slightly less than one thousandth of a per cent by volume. Tracer helium was added to the injected gas during two separate periods, the first of about fourteen days duration and the second of about thirty days duration. An approximately two-week interval was interspersed between the two periods of helium addition. During the first period, helium was added to bring the total helium content to approximately 0.14 per cent and during the second period, helium was added to bring the total helium content to approximately 0.05 per cent by volume. We were unable to differentiate between arrival of the first and the second waves of tracer-laden injected gas at the producing wells. A much longer interval between successive waves will be allowed in subsequent tests in other fields.

Before referring to the next figure, I want to call your attention to the four offset wells approximately equidistant from the injection well. The next several figures show the helium content data of produced gas from the surrounding wells, and the first four graphs shown are data from these four offset wells.

● **Fig. 2.** This figure presents data on two of the wells offsetting the injection well. These data reval that tracer helium arrived at the one well approximately five days after start of helium-addition, and arrived at the other well approximately 22 days after start of helium-addition. It is noticeable that the helium content of the produced gas after arrival

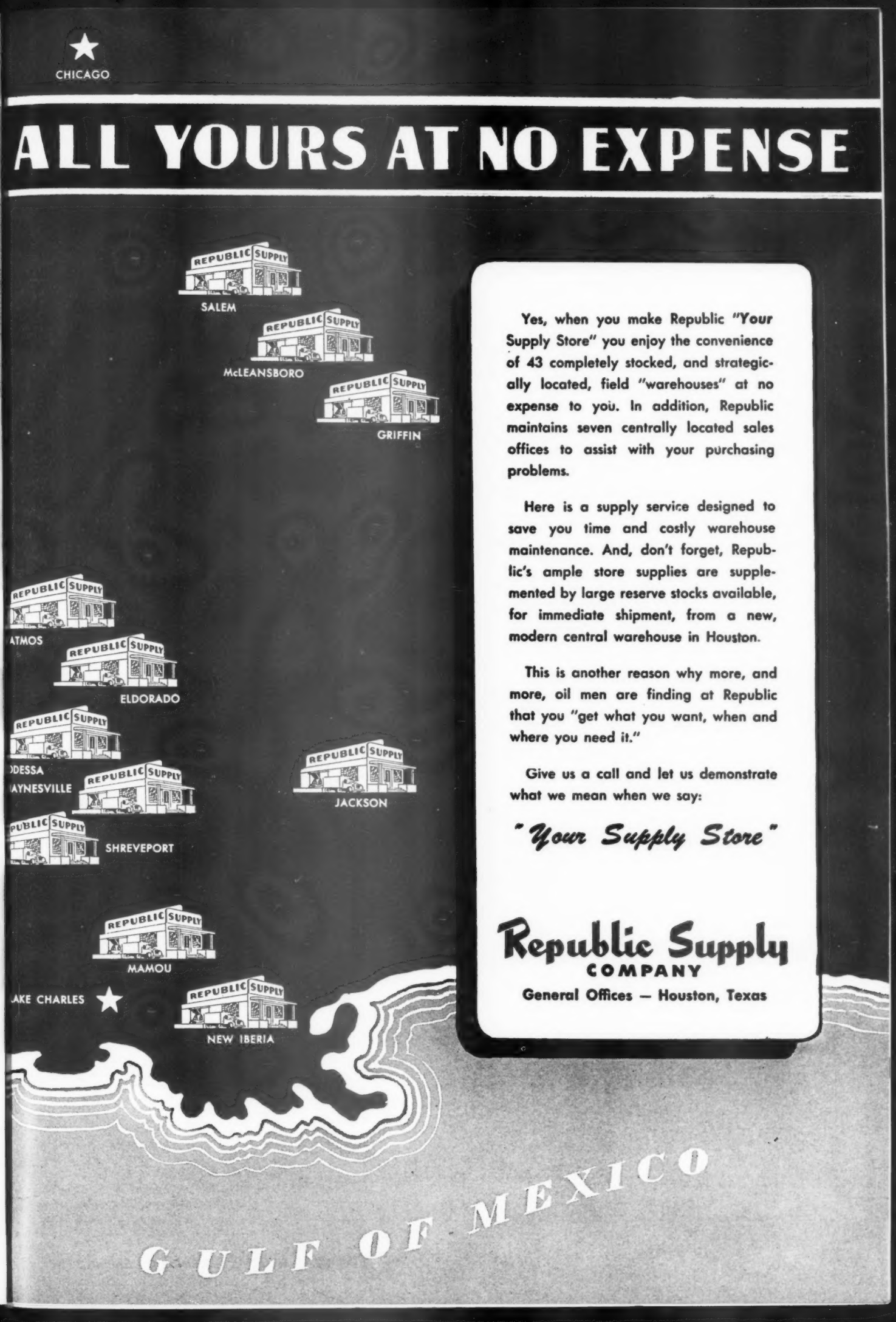

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FIG. 5.

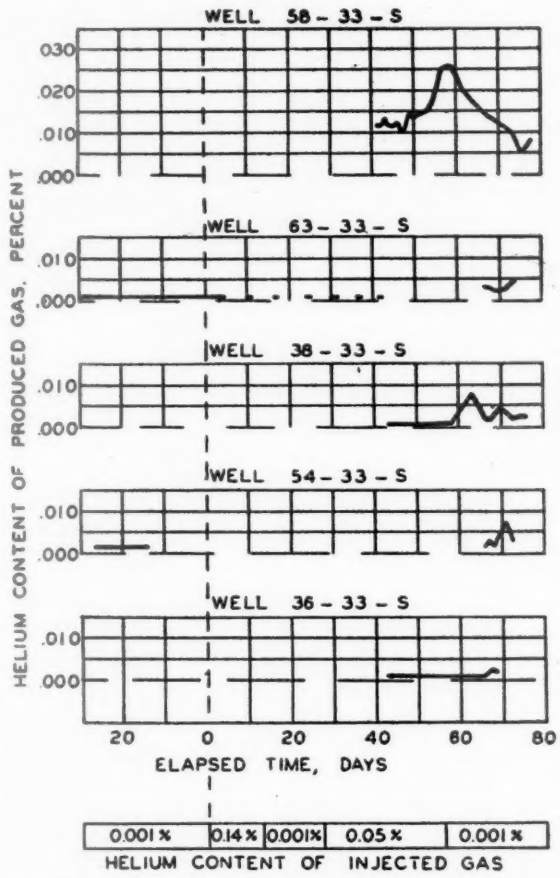
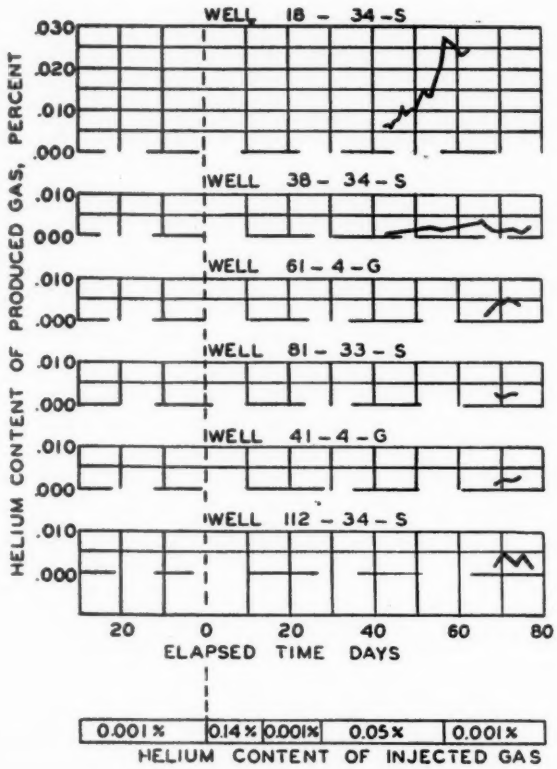
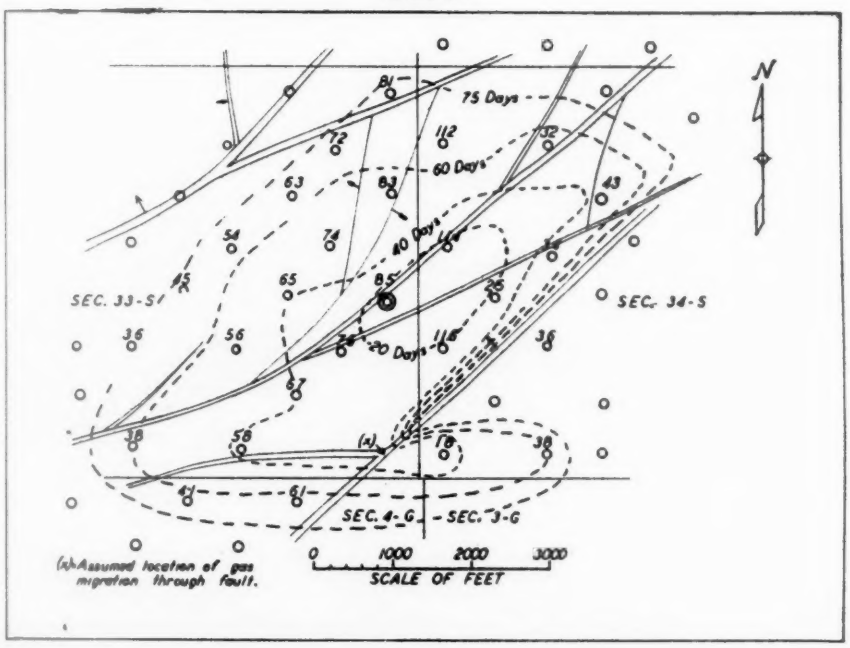

WELL 58 - 33 - S
WELL 63 - 33 - S
WELL 38 - 33 - S
WELL 54 - 33 - S
WELL 36 - 33 - S
HELIUM CONTENT OF PRODUCED GAS, PERCENT
.030
.020
.010
.000
20 0 20 40 60 80
ELAPSED TIME, DAYS
0.001% 0.14% 0.001% 0.05% 0.001%
HELIUM CONTENT OF INJECTED GAS

FIG. 6.


WELL 18 - 34 - S
WELL 38 - 34 - S
WELL 61 - 4 - G
WELL 81 - 33 - S
WELL 41 - 4 - G
WELL 112 - 34 - S
HELIUM CONTENT OF PRODUCED GAS, PERCENT
.030
.020
.010
.000
20 0 20 40 60 80
ELAPSED TIME DAYS
0.001% 0.14% 0.001% 0.05% 0.001%
HELIUM CONTENT OF INJECTED GAS

of the tracer-laden gas varies widely from day to day. This variation in helium content has not been encountered in other projects; and a probable explanation for the variations in the Elk Hills work has been obtained only relatively recently. Our tracer work was closed down prematurely due to the closing in of the field following VJ day. The injection well and all the producing wells under observation were open to two separate zones. Observations coming to our attention subsequent to the preparation of our report indicate that the injection well had caved at the lower zone. This probably caused most of the injected gas, including the tracer-laden gas, to enter the upper zone while gas at the producing wells came from both zones. Variations in the producing rates as well as other factors could cause easily the wide variations in the helium content of the produced gases.

FIG. 7.



● **Fig. 3.** This figure shows helium content data of additional wells. The two upper graphs show data from the two additional offset wells near the injection well. Tracer helium arrived at the third well after approximately 30 days and at the fourth well after approximately 55 days. Thus the time required for the injected gas to travel approximately equal distances in the four directions was 5, 22, 30, and 55 days respectively.

The additional graphs on this figure are for wells farther away from the injection well. In the case of the fourth graph, sampling of the well was discontinued after the first few days, for some reason that I do not remember, and was not resumed until late in the project —apparently not until after tracer helium had arrived in the vicinity of the well.

● **Fig. 4.** This figure shows helium content data of additional wells. Collection of data on two of the wells was interrupted during a part of the study, thus accounting for the breaks in the graphs.

In the preparation of the graphs showing helium content data, the wells were

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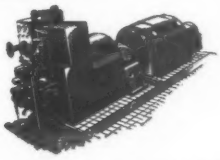

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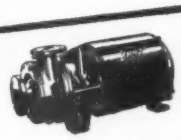

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FIG. 8. Typical data from the Cabin Creek, West Virginia, field.

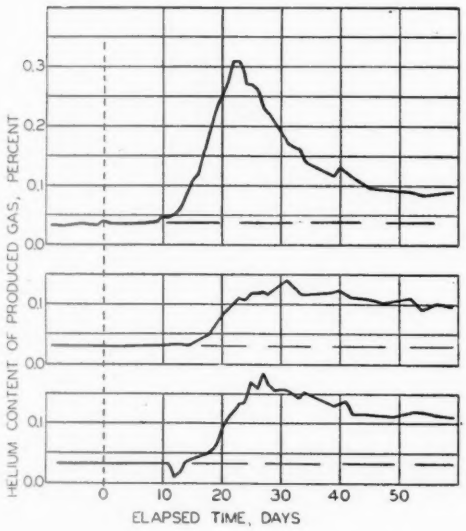


FIG. 9. Typical data from the Cabin Creek, West Virginia, field.

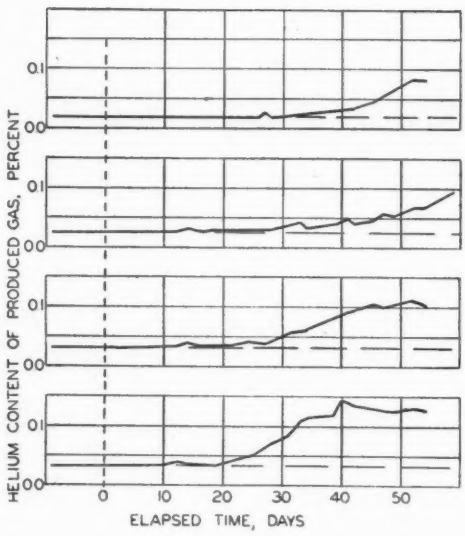
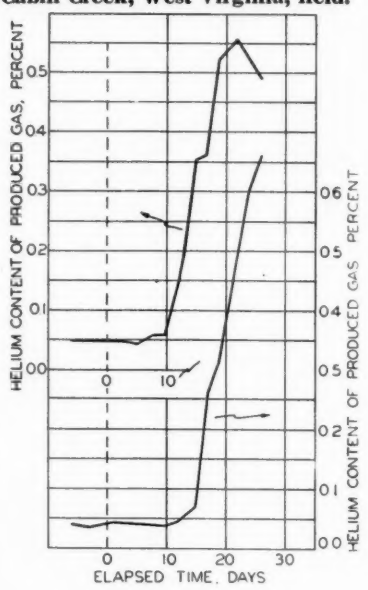


FIG. 10. Typical data from the Cabin Creek, West Virginia, field.



grouped roughly in accordance with their relative nearness to the injection well. As the tracer helium was detected at the nearer wells, additional wells farther out were selected for sampling. Accordingly, in the subsequent graphs, data are missing for the earlier part of the study, and in several instances, the tracer helium already had arrived before the sampling was begun. Though the data are fragmentary in places, they are included to give the complete picture of our Elk Hills helium tracer work.

● **Fig. 5.** Helium content data of additional wells are shown in this figure.

● **Fig. 6.** Helium content data of additional wells are shown in this figure. Attention is called particularly to the first two graphs on this figure, as these play an unusual part in subsequent interpretations. Helium appeared at the well first shown several days earlier than at the second, and in much greater concentration. Data on the additional wells are fragmentary and probably indecisive except that they indicate that tracer helium had arrived. It was our intent to follow the wave of tracer-laden gas much farther and thus obtain more data on these additional wells, but the closing in of the field following VJ Day prevented our doing so.

● **Fig. 7.** After preparation of the preceding graphs, the best estimate was made of the time of arrival of the tracer-laden injected gas at the various producing wells. Fig. 7 then was prepared showing the best estimate of the position of the wave-front of tracer-laden injected gas at the end of 20, 40, 60, and 75 days subsequent to start of addition of tracer helium to the injected gas. During the discussion of previous figures, attention was called to wells 18 and 38, at the lower right portion of Fig. 7. The present interpretation of the break-through at (x) is based on the early arrival at 18 compared to 38, the much stronger show of tracer helium at well 18, and the probability of more extensive fracturing of the formation at the intersection of the major and the minor faults.

● **Fig. 8.** The Bureau at the present time is conducting a helium tracer gas project in the Cabin Creek, West Virginia, oil and gas field. This project is incomplete, though progressing satisfac-

FIG. 11. Helium analysis apparatus.

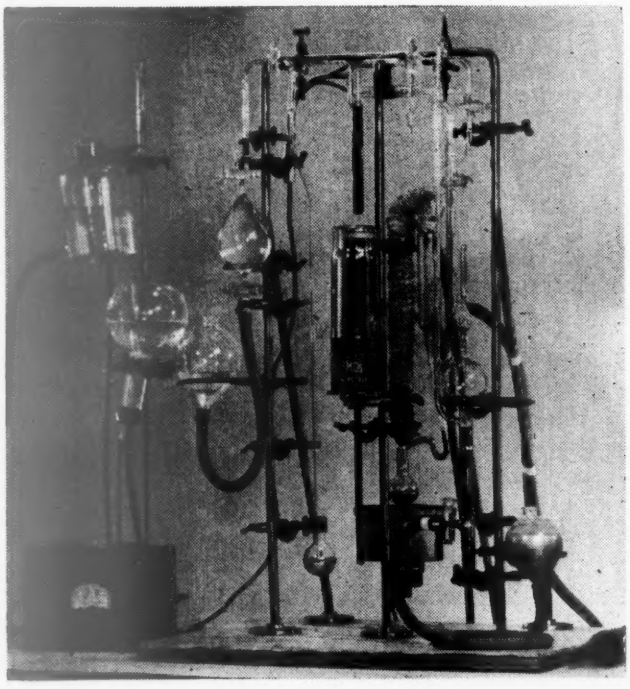
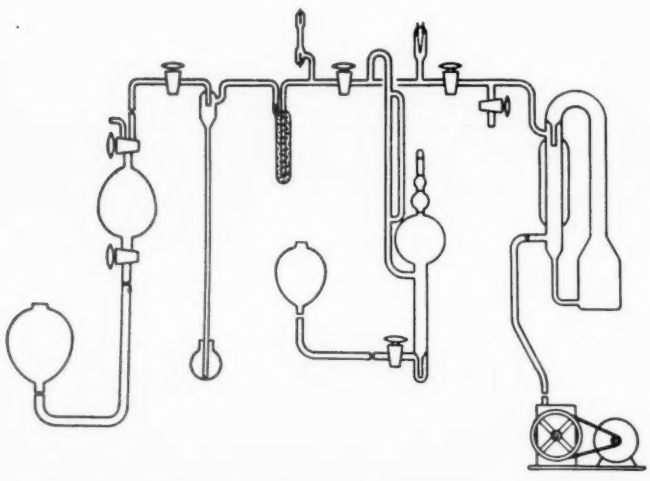


FIG. 12. Schematic drawing of helium analysis apparatus.



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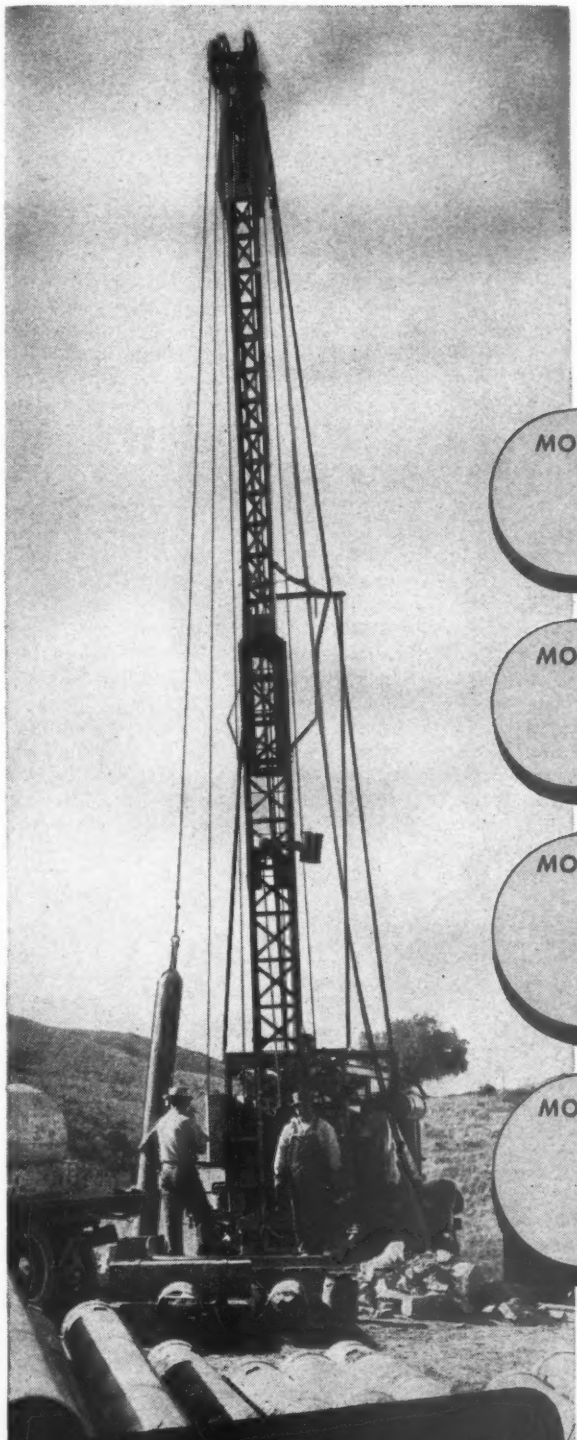

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torily, and no report has as yet been written on it. Data on a few typical wells are given in the present paper, however, to show the success with which we are detecting the arrival of tracer helium at the producing wells. During this test, tracer helium was added to the injected gas for one week, and in quantity sufficient to raise the helium content of the injected gas from about .03 per cent to one per cent, following which the addition of helium was discontinued. Observation of gas from the surrounding producing wells still is in process. One outstanding feature noticeable from the graph is the length of time the tracer helium persists at the producing wells compared to the length of time during which helium was added to the gas. In some instances, the wave already has persisted for more than fifty days and shows no signs of receding within the near future. Fig. 8 shows data from a few typical wells.

● **Fig. 9.** Additional typical well data from the Cabin Creek project are shown in Fig. 9.

● **Fig. 10.** Additional typical well data from the Cabin Creek project are shown in Fig. 10.

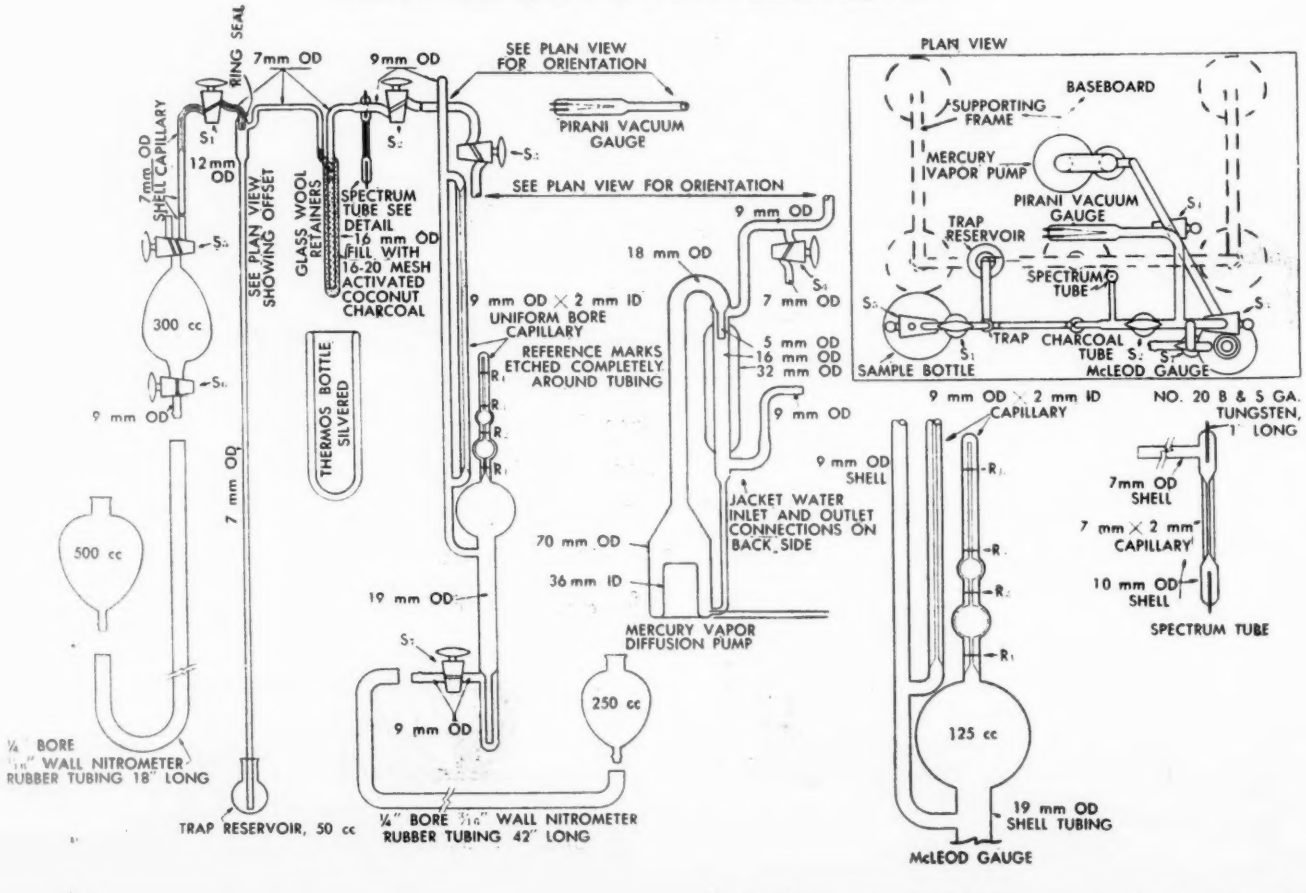
● **Fig. 11.** The Bureau has developed a helium analysis apparatus recently that is portable and in addition has a sensitivity much greater than that possessed by former apparatus. A photograph of the apparatus is shown in Fig. 11. Gas formerly reported as having no helium content often can be analyzed readily and the low helium content determined with appreciable precision when using the new apparatus. Duplicate samples have been analyzed and results obtained that check to a thousandth of a per cent. In several instances, results have been obtained that check to one ten-thousandth of a percent, though this precision is not often required and does not seem to be of practical importance in helium tracer work. An apparatus of this type has been carried several thousand miles in the back seat of an ordinary passenger automobile without breakage. This portability permits taking the apparatus to the field for use in tracer work instead of requiring that the samples be shipped to a central laboratory. The only accessories required in the field are a source of electric energy, a very small volume of tap water, and a source of liquid air or liquid nitrogen. The liquid air or nitrogen may be shipped appreciable distances. A skilled operator can run fifty or more analyses a day under ordinary conditions.

● **Fig. 12.** A schematic diagram of the helium analysis apparatus is shown in Fig. 12. The apparatus is based upon the fact that large volumes of all constituents except helium normally found in natural gas are adsorbed quantitatively on activated coconut charcoal that is cooled to the temperature of liquid air. The apparatus comprises a sample measuring bulb, a charcoal-filled tube that during operation is cooled with liquid air, a McLeod gage for measuring the pressure produced within the apparatus by the helium in the sample, a spectrum tube for assuring that all gases except helium have been adsorbed, and a vacuum pump for exhausting the apparatus preliminary to an analysis and between successive analyses. Details of construction, calibration, and operation of the apparatus are given in Bureau of Mines Report of Investigation No. 3899. The apparatus is available at the present time only on special order from glass-blowing shops, of which there are many making equipment of this type.

● **Fig. 13.** Report of Investigation No. 3899 contains a complete working drawing from which the apparatus may be built. This working drawing is shown in Fig. 13. We have been able to purchase several sets of the apparatus complete with all accessories at a cost of less than $500 per set.

● **Fig. 14.** Three types of helium shipping containers are used on a routine basis by the Bureau. These comprise the small cylinder, approximately 9 in. in diameter and 5 ft tall, containing approximately 200 cu ft of helium at a pressure of approximately 2000 psi; a motor transport trailer containing about 30,000 cu ft of helium at about 2400 psi; and railway tank cars containing approximately 200,000 cu ft of helium at about 2400 psi. The small cylinder is familiar to most of us, particularly as the oxygen cylinder used in welding. Special valves are used for helium service, though.

FIG. 13. Working drawing of helium analysis apparatus.



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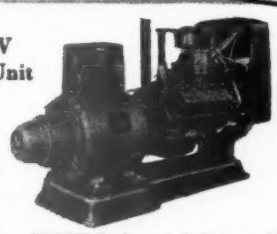

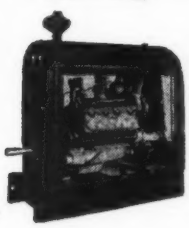

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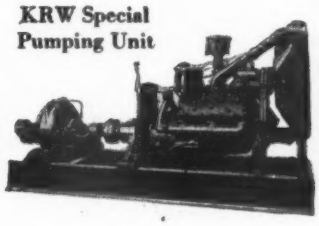

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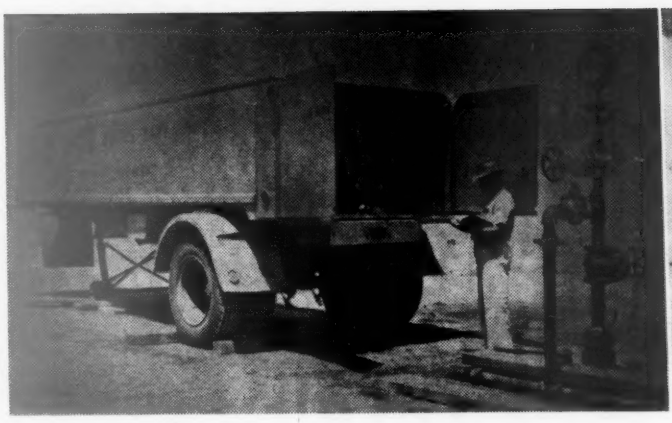

FIG. 14. Motor transport helium trailer.

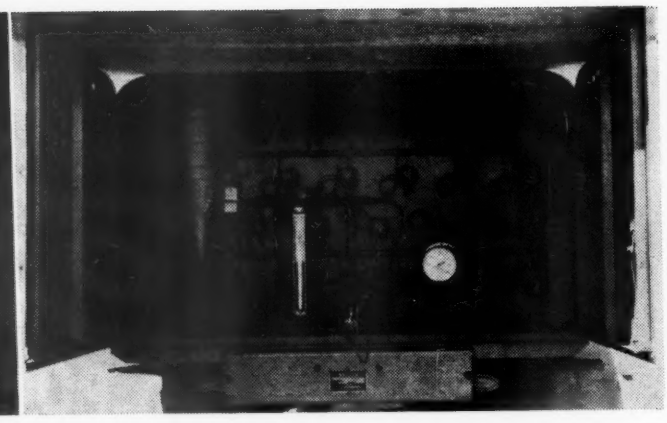

FIG. 15. Manifold end of motor transport helium trailer.

FIG. 16. Railway helium tank car.

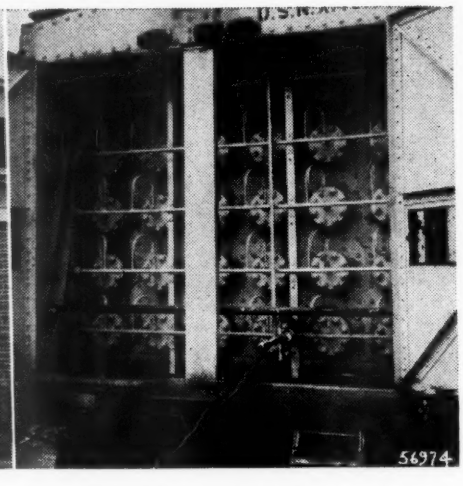

FIG. 17. Manifold end of railway helium tank car.

One of the motor transport trailers is shown in **Fig. 14** and a close-up of the manifold end in **Fig. 15.** The various cylinders comprising the trailer are manifolded together to provide a single outlet line for discharging the helium. Accessories visible in this figure are the orifice run and "U" tube for controlling the rate of low-pressure discharge from the trailer. One of the railway tankcars is shown in **Fig. 16,** and a close-up of the manifold end of the tank car is shown in **Fig. 17.** Here again the various cylinders are manifolded to provide a single discharge line for the helium.

The Bureau has for years carried on a survey of natural gases with particular reference to helium contents in their search for fields containing commercial quantities of helium. In the course of this survey many wells from many different fields have been analyzed, and since the start of the helium tracer studies, many more have been analyzed. It has been found that the helium content of gas varies from field to field even when closely associated and that the helium content of gas from different wells in the same field varies. Two adjacent wells may not necessarily have the same helium content. The numerical value of the variation among samples from different wells in the same field may not be large, but often on a percentage basis the variation is appreciable. The wells of some fields have been under observation for nearly twenty years and no tendency has been noted for the helium contents of gas from the various wells to approach a common level. The reason for this variation is not understood, and, frankly, neither is the process understood by which the helium originally gets into the gas. Several theories have been advanced, but none seem conclusive. Thus, it should not be surprising if in the course of surveys preliminary to a tracer project, it is found that the helium contents of gas from all wells in a single field do not agree.

Helium is available readily to commercial users within the United States. The Bureau is in a position to release several million cubic feet a month after meeting all military needs. This surplus helium is being extracted from natural gas that already has been produced from the ground and is enroute to commercial markets. If the helium is not extracted and used, it is lost forever. The Bureau would welcome the opportunity to make this surplus helium available to American industry, for it is a resource not possessed so far as is known by other countries.

Helium is sold by the Bureau of Mines for medical, scientific, and commercial use under regulations approved by the President. The present sale price for commercial helium is $13 per 1000 cu ft, f.o.b. the helium production plant when delivered into tank cars, semitrailers, or large multiple-cylinder units, and $15 per 1000 cu ft when delivered into standard cylinders. The Bureau is in a position to make available to the purchaser tank cars, semitrailers, or standard cylinders at nominal rental rates. Helium may be shipped in the purchaser's containers provided they meet with Bureau of Mines and Interstate Commerce Commission specifications. Copies of the regulations governing the production and sale of helium are available upon request from the Bureau of Mines, United States Department of the Interior, Washington, D. C.

It is hoped that helium used as a tracer will give the oil and gas fraternity a new tool with which to explore the underground movement of fluids accurately. The Bureau has taken the initiative in arranging and conducting the first few field projects, developing this new use of helium, and is prepared to cooperate actively with operators to the extent of its available resources in the further utilization of helium as a tracer gas.

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Pumping equipment selection for secondary recovery developments*

By E. N. Kemler, Southern Research Institute

● **Abstract.** Secondary recovery pumping equipment selection generally differs from primary recovery equipment only in size. This paper gives a summary of data on horsepower requirements available on small and shallow wells. Information on rod-line power losses is likewise given. In the rational use of pumping equipment on small wells, every effort should be made properly to apply and counterbalance such wells. Proper counterbalancing is also a most important factor to be considered when applying used equipment to secondary recovery projects, or in putting existing equipment to heavier service. Proper counterbalance is equally important on central powers and beam wells.

*Presented before American Petroleum Institute, Division of Petroleum, Chicago, Illinois, November 12, 1946.

● **Introduction.** The preparation of a paper on pumping equipment selection for secondary recovery developments is rather difficult, because each individual case has certain characteristics that require separate consideration. In general, secondary recovery projects require the most careful conservation of investment, in order to have reasonable payout or return on investment. This usually dictates the utilization or adaptation of existing production equipment whenever possible. A general discussion of this question requires: First, a consideration of the problems of selecting equipment where new equipment will be used; and, second, a consideration of the factors involved in the utilization of existing or second-hand equipment when it is either available or advisable to use it because of economic circumstances. In the general development of this subject, therefore, the material will be treated first from the standpoint of selecting new equipment, which involves power and load characteristics, together with the discussion of methods of calculating these values. A discussion of torque requirements and counterbalancing follows. Those factors that are involved in utilization of existing or second-hand equipment are very similar; however, the discussion on this point is more concerned with means of obtaining the most from such equipment, inasmuch as the utilization of this second-hand equipment is at a heavier load requirement, in general, than that for which the equipment is used prior to the secondary recovery use.

The material as given herein is further limited to discussion of general prin-

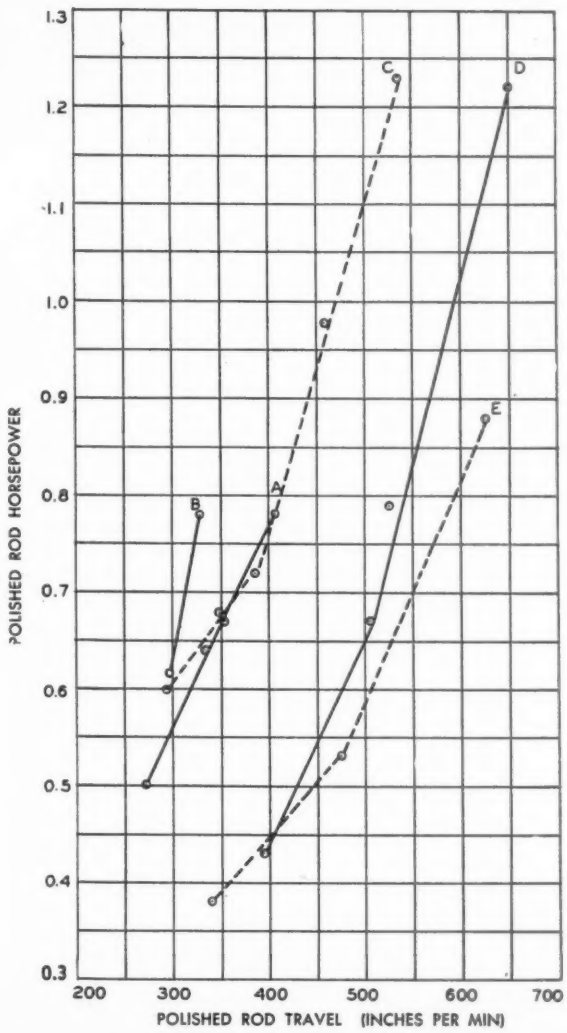


FIG. 1. Polished-rod horsepower 1000 to 1500-ft wells. Diameter of plunger, 1¾-in.

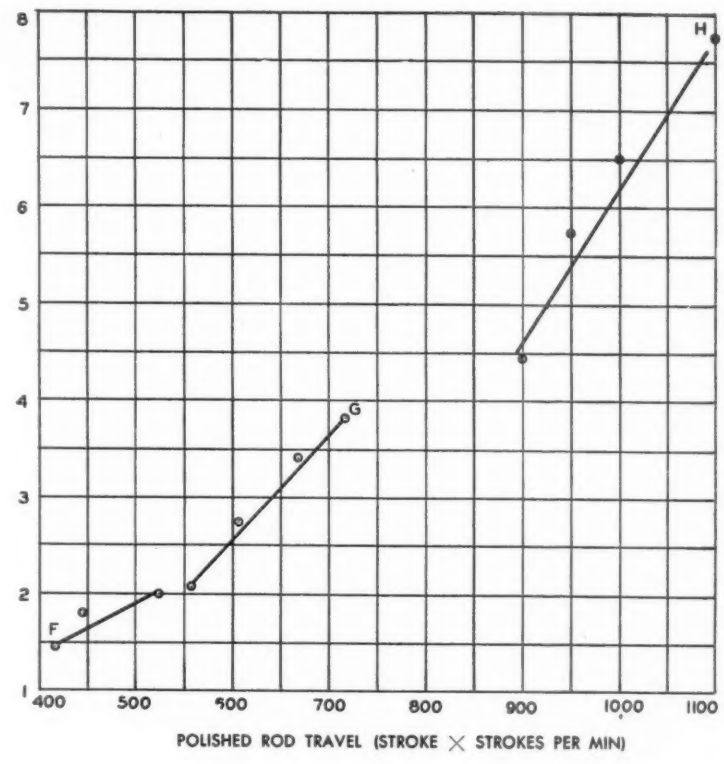
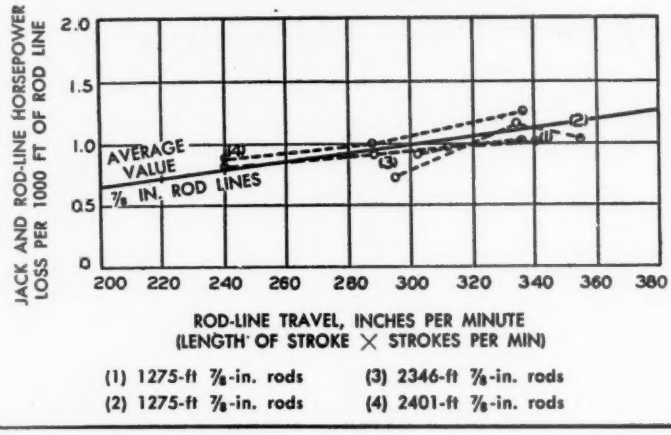


FIG. 2. Polished-rod horsepower 2500-ft wells; 1¾-in plunger.

FIG. 3. Jack and rod line horsepower vs rod line travel, in inches per minute.


JACK AND ROD-LINE HORSEPOWER LOSS PER 1000 FT OF ROD LINE
2.0
1.5
1.0
0.5
0
AVERAGE VALUE
⅞ IN. ROD LINES
200 220 240 260 280 300 320 340 360 380
ROD-LINE TRAVEL, INCHES PER MINUTE
(LENGTH OF STROKE × STROKES PER MIN)
(1) 1275-ft ⅞-in. rods
(2) 1275-ft ⅞-in. rods
(3) 2346-ft ⅞-in. rods
(4) 2401-ft ⅞-in. rods

ciples rather than to any specific equipment. The types of equipment that are generally available under various circumstances vary from area to area as well as from manufacturer to manufacturer, so that any discussion of this type of equipment is rather difficult on a generalized basis. The material that is given herein can be adapted to a wide range of applications, depending upon the particular circumstances involved. Although the data included are meager, they represent the limited information available. Because small wells are generally operating on a marginal basis, the engineering analysis of such wells has generally received very little consideration, so that a very minimum of information is available as compared with the larger wells utilizing heavier equipment.

● **Selection of new equipment.** In the selection of equipment for the pumping of wells, consideration must be given to the power requirements, the peak-load requirements, and the peak-torque requirements. The power requirement detemines in part the size and characteristics of the prime mover. The peak-load requirement fixes the size of the structural members, and the size of the rods needed. The peak torque required by the cycle determines the size of the transmission needed, including the clutch, belts, gears, or chains, and the shaft sizes. In the application of stock sizes of pumping equipment, the engineer must be certain that the equipment can handle the peak loads and torques. Although these peak values are dependent on the pumping cycle, the rod sizes, and the pump size, they can also be influenced by the design of the installation, and by the care used in the counterbalancing of the system. By proper counterbalancing, the size of installation required can be considerably reduced. Likewise, by failure to maintain a pumping system in proper counterbalance, the equipment can become greatly overloaded. The operator of equipment can influence the peak torque on equipment by a factor of 2 to 1, depending on the amount of counterbalance used and the care used in properly counterbalancing. The size of equipment to give long trouble-free service will then largely depend on whether the operator wishes to select on the basis of properly counterbalancing and maintaining this counterbalance, or on the basis that no attention will be given to this important factor.

● **Power requirements.** The following information on load and power requirements is largely based on actual well tests on small wells comparable to those encountered in secondary recovery operations. The limited amount of data on such wells makes it necessary to give only average conditions. Inasmuch as power and load requirements depend on so many factors, it is difficult to cover more than the normal conditions to be encountered. The effect of improper alignment of rod lines, improperly lubricated or located swings and holdups or holddowns, crooked holes, improperly sized pumps, and similar factors will leads to higher loads and power requirements.

Fig. 1 lists data taken in 5 wells covering a wide range of pumping cycles.[1] These data cover the general range of conditions that might be expected in wells between 1000 ft and 1500 ft. For shallower wells there are few data available, so that any prediction of horsepower requirements must be an estimate. Fig. 2 shows representative data on 2500-ft wells as shown by three series of tests. These data show that horsepower requirements tend to increase more rapidly than they would to maintain a direct proportion to pumping speed.

In central power installations rod-line losses constitute a very important factor in determining the entire power requirements. Power loss in rod lines is difficult to evaluate, as it varies with rod size, speeds, type, and spacing of carriers, profile of the line, and other physical factors. Fig. 3 gives some representative data for ⅞-in. rod line.[1] This diagram gives rod-line loss per 1000 ft of line for representative pumping speeds or rod-line travel. For moderate pumping cycles the loss is about 1 hp per 1000 ft of line.

The total power requirements of a central power installation must include the sum of polished-rod horsepower and rod-line horsepower. When there is an excessive number of swings, dummies, holdups or holddowns, some allowance must be made for them. Friction losses in rod lines or pumping wells can result in much higher horsepower requirements than indicated.

● **Load.** Polished-rod loads may vary as much as polished-rod horsepower. Friction of the rods and plunger probably account for the greatest part of this variation. Unless dynamometer data are available, the best estimate of peak load can be obtained for the Slonneger formula:

$$\text{Load} = (W_r + W_o)\left(1 + \frac{NL}{5400}\right)l$$

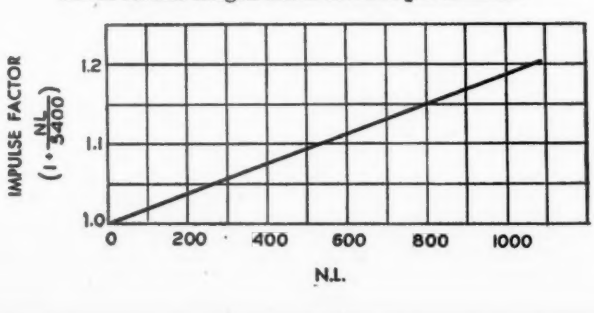
Where:

W_r = weight of rods per ft.
W_o = weight of oil column on plunger per ft.
N = strokes per minute.
L = length of stroke, in.
l = depth of well.

For a 1⅝-in. rod string and 1¾-in. plunger, $W_r + W_o$ is approximately equal to 2.2 lb per ft. Fig. 4 gives the quantity $1 + \frac{NL}{5400}$ for various products of NL.

● **Balancing.** Balancing of wells is most easily accomplished in the field[2, 4, 5]. Many discussions of methods of counterbalancing are to be found in the literature. The simplest and easiest applied method is that of slipping the clutch. This method has been described a number of times in the literature, and consists merely of gradually releasing the clutch on a pumping well until it starts slipping on either the upstroke or downstroke. If the clutch slips equally

FIG. 4. Relation of impulse factor to product of stroke length times strokes per minute.



on the upstroke and downstroke, it means that the well is properly counterbalanced. If it slips more on the upstroke than on the downstroke, it means that the well is underbalanced; and, if it slips more on the downstroke than on the upstroke, it indicates that the well is overbalanced. With a little experience, operators can soon learn to do a good job of balancing by using this method. The emphasis on balancing may seem to be out of place in an article of this type; however, balancing is so important in obtaining the maximum from equipment that it cannot be overemphasized. A little underbalance or overbalance is equivalent to underloading or overloading the equipment. The difference between no balance and perfect balance on a small well may mean the difference in peak load or torque on the equipment by a factor of 2, or even 3 or more, to 1. Therefore, unbalance even to a small degree can have the effect of a 30 per cent or 40 per cent increase or decrease in torque.

The counterbalancing of central powers is equally as important as that of individual wells. The effect on the prime mover and on the central power itself is as destructive as on an individual unit; however, the counterbalancing of such wells is somewhat more difficult; and, inasmuch as counterbalance cannot be used on individual wells and still maintain good rod-line operation, the use of dummies is necessary. To calculate the position and amount of dummies is somewhat more difficult, and requires calculations based on well loads and positions. Several methods have been proposed in the literature that are entirely satisfactory for work of this type[3].

Through the use of good engineering practices, it is frequently possible to utilize old equipment satisfactorily; however in many cases such equipment, if not properly engineered, and if not kept in proper balance and condition, will give excessive trouble. A little effort in balancing and alignment can mean much in improved service. These practical factors are generally more important than some of the theoretical considerations with regard to type of equipment to be used or the method of operation. As indicated previously, loads increase more rapidly than in direct proportion to pumping cycle. Therefore, every effort should be made to size equipment and control operating conditions to obtain as slow a pumping cycle as possible. This again is particularly important when old equipment is utilized, because, in general, it does not have so large a factor of safety as when new.

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5. Emory N. Kemler, *op. cit.*, 103-4, discussion by D. O. Barrett.

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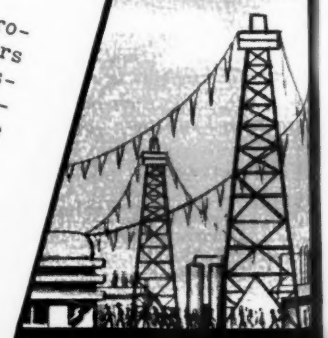


TULSA, OKLAHOMA, U.S.A., MAY 15-22, 1948

Corrosion and preventive methods in Katy field*

By R. C. BUCHAN, Humble Oil and Refining Company

● **Abstract.** The author describes briefly the Katy gas-condensate field, the producing and cycling equipment used, and its operation. The effects of acidic-water corrosion are illustrated and discussed. The use of plastic-coated pipe, and the use of soda ash as a neutralizing agent, are described as being practical means of reducing corrosion losses in the Katy field. The need for continued research and for field testing of alloys is pointed out. Instead of waiting for a complete understanding of such problems, it is advocated that full-scale field tests be initiated as soon as corrosion is found in new fields. The arrangement of sub-surface equipment to facilitate corrosion control is discussed briefly. The importance of keeping equipment in safe working condition is emphasized.

● **Introduction.** The corrosion of equipment used in producing condensate reservoirs is becoming an old problem in the industry. Most of the present knowledge pertaining to the subject has been well summarized in the form of tentative conclusions in a recent API paper.[1] Intensive efforts are being continued on this problem by committees under the sponsorship of the American Petroleum Institute (API), Natural Gasoline Association of America (NGAA), and the National Association of Corrosion Engineers (NACE). Additional work is being done by the U. S. Bureau of Mines, and by the research and operating departments of the producing companies.

It is the purpose of this paper to present the specific problem encountered in one of the larger condensate fields, and to discuss the problem essentially from an operating viewpoint.

Long periods of research are in prospect. Because of the numerous unevaluated and possibly some unrecognized variables connected with the problem, and because of the apparent inconsistency of the observed phenomena, a major effort should be directed toward full-scale field experiments. This is being done in the Katy field; and, although all corrosion is not under control, a reasonably early solution of the problem in that field appears likely.

The Katy gas-condensate field, located in Waller, Harris, and Fort Bend counties about 30 miles northwest of Houston, Texas, is an oblong domal structure covering an area of approximately 30,000 acres. The average well depth is 7600 ft. The formation between 6250 ft and 7450 ft below sea level is divided into six separate sand reservoirs — each of which consist of one or more lenticular members. The porosity of the sands varies from 18 to 35 per cent. Each reservoir has a definite water table, and producing wells are completed well above the gas-water contact.

The field was discovered in 1935, and developed rather slowly. A cycling plant was put into operation in January, 1943, and an absorption plant was added later in 1943. The entire field was unitized, and the plan was enlarged in 1944. The present major facilities in the field consist of: 33 producing wells, 36 miles of gathering lines, an absorption-compressor plant, 34 miles of injection lines, and 13 injection wells. Almost all the equipment and materials selected are those suitable for the working pressures encountered in a non-corrosive, non-abrasive service.

The producing wells were initially completed with either 7-in. or 5½-in. OD oil-string casing and with 2½-in. or 2-in. tubing, set without packers so that wells could be produced from both the casing and tubing. Surface casing, 10¾-in. or 9⅝-in. OD, was set at a depth of at least 2500 ft in all wells. Producing wells were equipped with 6000-psi test wellhead assemblies, which included adjustable chokes with 1-in. ID beans on the tubing and casing outlets. Injection wells are equipped with tubing and with 10,000-psi test wellhead assemblies. Figs. 1 and 2 illustrate typical wellhead assemblies.

The gathering system is of welded construction, and consists of nine main lines into which the individual well lines are connected, usually at right angles. The pipe size varies from 4 in. to 10 in., but most of it is 8 in. Lines were tested to at least 3100 psi with water, after installation. The pipe sizes in the injection system vary from 4 in. to 12 in., and were tested to 4100 psi. No lines were doped and wrapped. Cathodic protection is not used except in the plant area to protect lines in the plant.

The absorption-compressor plant was designed for an absorber pressure of 1800 psi. The actual pressure used varies between 1800 psi and 1850 psi, and the lean gas is compressed to 3150 psi for injection.

Six-in. lines and meters are used at injection wells, and these are connected to 3-in. or 4-in. wellhead fittings.

● **Operation of the field.** Until January, 1943, wells remained shut in, or were produced at low rates—mainly for

*Presented before American Petroleum Institute, Division of Production, Chicago, Illinois, November 13, 1946.

FIG. 1. Wellhead assembly on producing well.

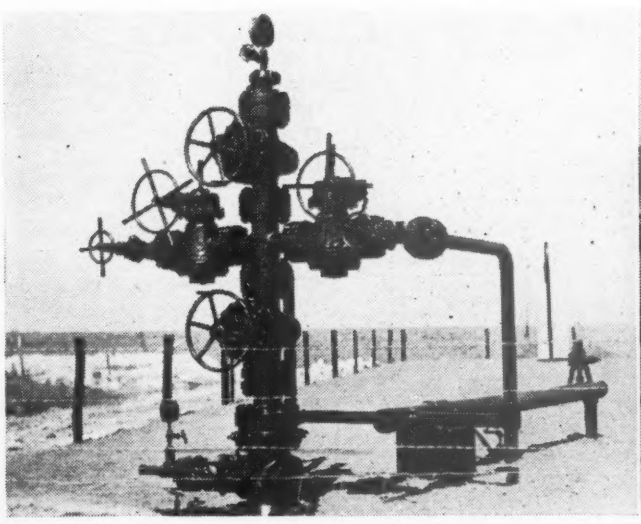
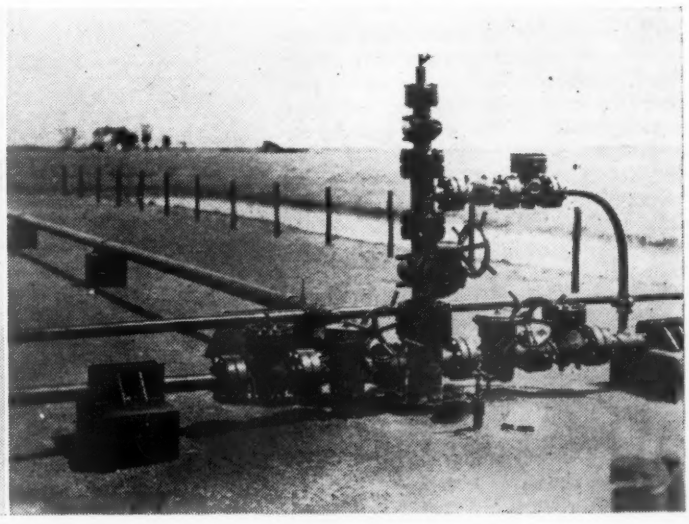


FIG. 2. Wellhead assembly on injection well.



fuel for drilling operations. From January, 1943, to April, 1946, wells were produced at fairly high rates through the casing and tubing. During this period the flowing wellhead pressures were between 2400 psi and 2630 psi; producing rates were 2 to 36 MMCF* per well per day (most were between 20 and 25 MMCF); and the wellhead temperatures were between 144 and 180 F (most were between 170 and 175 F).

During April, 1946, all production through the casing was discontinued, and work was accelerated to replace some of the corroded 2-in. and 2½-in. tubing with larger diameter tubing, in order to obtain the desired flow capacities without having to reduce the absorber pressure at the plant. Most of the new tubing installed was 4½-in. OD (4-in. ID) or 4-in. OD (3½-in. ID), externally upset with an insert joint to form an internally flush bore. The present flowing wellhead pressures are between 2100 psi and 2250 psi; producing rates are 7 to 32 MMCF per well per day (most are between 10 and 15 MMCF); and the wellhead temperatures are between 148 and 170 F (most are between 150 and 160 F).

The inlet pressure at the plant varies between 2000 psi and 2100 psi. The temperature of the gas entering the plant varies between 130 and 140 F.

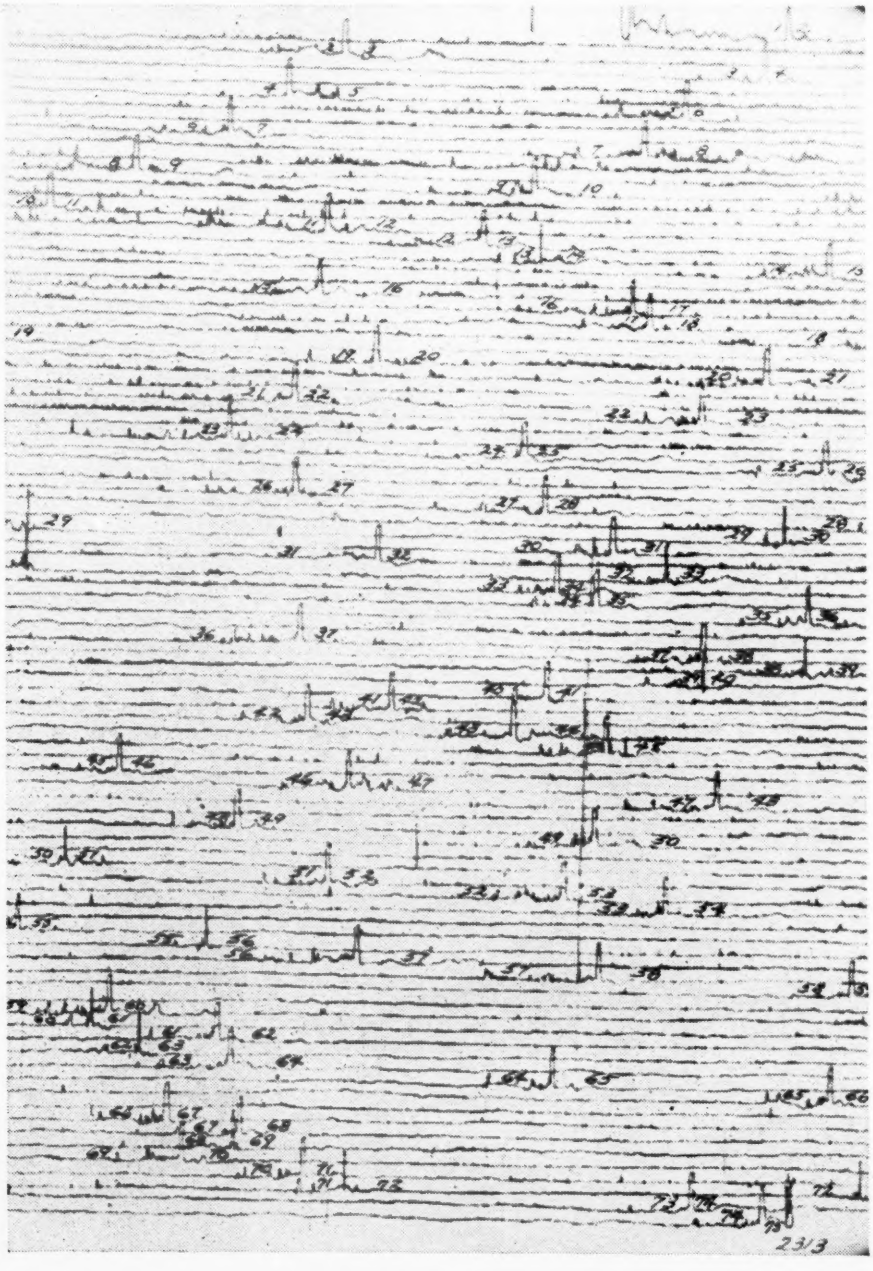
The gas is injected at a wellhead pressure of about 3025 psi, and at rates of 7 to 61 MMCF per well per day (most wells take 20 to 30 MMCF per day). The wellhead temperatures at injection wells vary from 100 to 155 F, and average 145 F. The average temperature of the gas leaving the plant is 160 F.

● **Equipment affected by corrosion.** Corrosion affects to some extent all casing and tubing strings subjected to well fluids. The ferrous surface equipment, including wellhead assemblies, meter runs, and the gathering systems, are corroding internally. Corrosion in the plant has been negligible; and, although conditions warrant periodic inspections, corrosion is a minor problem at present, and it is believed that it will not become serious. The casing is believed to be corroding externally as a result of battery currents between the casing and flow lines.

The corrosion of subsurface equipment is the most expensive part of the overall problem. Analyses of waters produced in 1943 indicated that corrosion was occurring in the wells, but the seriousness was not fully realized. During the past 12 months, 12 strings of tubing were pulled after an average service of three and one-half years, and only about 25 per cent was in suitable condition to re-install. Grade H-40 and J-55 externally upset, non-normalized API tubing was installed initially. Except for the removal of mill scale, the lower part of the strings has not been attacked by corrosion. The internal corrosion in the remainder of the strings does not follow any given pattern, except that usually the first 2 ft of the lower end of each joint corrode more rapidly and more severely than does the upper end or the middle of the joint. Fig. 3 shows the results of an internal caliper survey, which reflects the condition of tubing after three years of average Katy service. Complete inspections of the tubing removed from five wells shows that no pitting has occurred in the main body of the pipe to within 2 ft from the ends in three of the five strings, even though pits have penetrated more than 50 per cent of the wall in the upset and upset round-out areas. External corrosion of tubing in wells producing from both casing and tubing has been minor, except that couplings, as shown in Fig. 4, are usually pitted—some badly—and the exposed threads are attacked where water can stand. Mill scale appears to be completely removed in less than one year.

Little is known concerning the actual condition of casing in Katy wells. One string of 5½-in. OD full-length liner was pulled after having been in service 3.7 years. The lower half of this pipe was not visibly affected. Internal corrosion was found in the upper half, and the pitted condition resembled that occurring on the inside of tubing. Most of the pitting was concentrated in an area within 24 in. of the end of the down end of the joint. The top 1200 ft. of this string was severely corroded. A number of holes were present in the end of the joints in the threaded section, and approximately ½ in. of the ends of several joints had corroded away as illustrated in Fig. 5. No external corrosion was found on this pipe, because it had been set inside of a 9⅝in. OD string that extended to about 7000 ft. (The external corrosion apparent in Fig. 5 was due to atmospheric cor-

FIG. 3. Chart from internal caliper survey at Katy field in tubing used three years.



*MMCF = million cubic feet.

FIG. 4. Corroded tubing coupling

FIG. 5. Corroded 5½-in. liner.

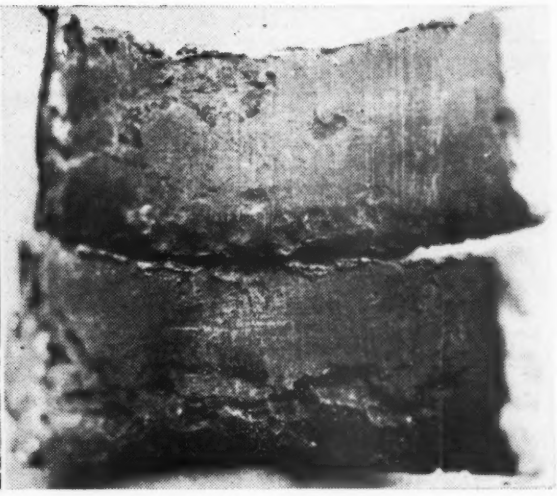


FIG. 6. Internal corrosion of casing.

rosion subsequent to removal from the well.)

Internal casing corrosion in the form of pitting has been found in other wells when wellhead equipment changes were made. Fig. 6 shows the condition of a piece of casing removed from just below the well head. Suitable tools for determining the extent of internal casing corrosion have not been available. Several recently developed tools will probably be tried at Katy as soon as the tools are available.

Corrosion and subsequent leakage made it necessary to replace almost every wing valve installed initially in well heads on producing wells—some after less than two years' service. The throats and the flange facings are most seriously attacked. The design of these valves needs no improvement, but corrosion-resistant materials are needed. Valves lined with several types of stainless steels or with Stellite have given perfect service with no apparent corrosion after more than two years' use. Some of the other alloys used for lining appear to be no more resistant than the ordinarily used steels. The shortage of valves known to be satisfactory in this service has dictated the use of 10,000-psi test valves to obtain the added corrosion tolerance.

Parts of choke assemblies used on producing wells are frequently replaced. Corrosion and erosion of the stems and beans prevent a tight closure, usually after about 30 days. Stems and beans are replaced every five or six months, because after that time their condition is such that they cease to serve their intended purpose. Hard surfaces, such as are obtained by lining with Stellite and hard electroplated chromium, have been proved to resist this erosion. Because only parts of the surface need protection against erosion, and because such linings are difficult to apply to the entire assembly, the base metal needs to be a corrosion-resistant material.

Other parts of well-head assemblies are corroding. Fig. 7 illustrates the nature of corrosion on ring-joint flanges. Because of general present lack of any proven material that is not too expensive, the present program includes the use of 10,000-psi test equipment, which provides additional corrosion tolerance. Plastic coatings are being tested in a number of wells; and, although a few of these coatings look promising, the cost of properly coated fittings is about the same as the cost of satisfactory alloys should be.

One of the more serious problems at Katy from a safety viewpoint is corrosion of ring gaskets. Fig. 8 shows a ring that had remained in service about two years. Synthetic-rubber "protection" rings are used to keep well fluids from having easy access to the ring gaskets. The rubber rings deteriorate and often disappear in three to four months, and the exposed ring gaskets corrode to an alarming degree in one year's time or less. So far, minor leakage has indicated failure, and replacements are made. Also, periodic inspections are made, and all rings that have been attacked are replaced. A program to try to find a better "protection" ring is in effect. Some of the available pastic materials appear suitable.

Katy is one of the six or seven fields in which a number of alloys are being tested by the NACE condensate well-corrosion committee. These tests should result in giving the industry a better selection of materials for combating corrosion in wellhead assemblies.

The corrosion that has been experienced in the gathering system has been confined to the inside bottom of lines, as shown in Fig. 9, except that, at tie-ins of individual well lines, erosion has aggravated corrosion as is shown in Fig. 10. Some parts of individual well lines have been replaced, and others probably will have to be replaced in the next year. Heavier pipe is being used for replacements. Test holes are used as an indication of loss of wall thickness. These holes have been drilled at all points where visual inspections have shown that a tendency toward corrosion exists. The holes are 1/16 in. in diameter, and drilled deep enough that a calculated safety factor of 1.15, based on minimum yield, still exists when corrosion allows the gas to break through the test hole. Radium inspection of critical locations in lines is also used to a limited extent. This has proved to be a satisfactory non-destructive spot-inspection method, provided two measurements 90 deg apart are made at each location so as to detect non-concentric pipe, and provided the individual method is accurate if an unknown amount of liquid is present. No external corrosion is experienced.

Corrosion in the gathering system is minimized by the chemicals used to protect subsurface equipment. The reduction in pressure and temperature over that existing a year ago may alter the rate of corrosion. The safety factor for bursting strength has been increased by the reduction of pressure.

No corrosion has as yet been found in the injection lines or injection-well equipment. This is as would be expected, because the gas contains 50 per cent or less water than the amount necessary for saturation entering the average injection wells. One injection well has a wellhead temperature of about 100 F, and no corrosion is being experienced—indicating an unsaturated condition at this lower temperature.

● **The cause of corrosion.** The internal corrosion of ferrous equipment at Katy is due to the acidic properties of the condensed water under the existing pressure and temperature conditions, as was pointed out by several investigators[2, 3, 4]. Carbon dioxide and organic acids are present. No doubt other substances are present, some of which probably increase, whereas some decrease, the corrosion rate, but the effect of no single substance has been isolated. The produced gas contains 0.6 to 0.7 per cent carbon dioxide. The condensed water at the plant inlet contains 390 to 400 ppm† of organic acids (as propionic acid), and about 150 ppm of iron. The pH of the water in the tubing has not been measured because of physical difficulties, but it is believed to be about 4.

Thorough studies of data from individual wells have not resulted in determin-

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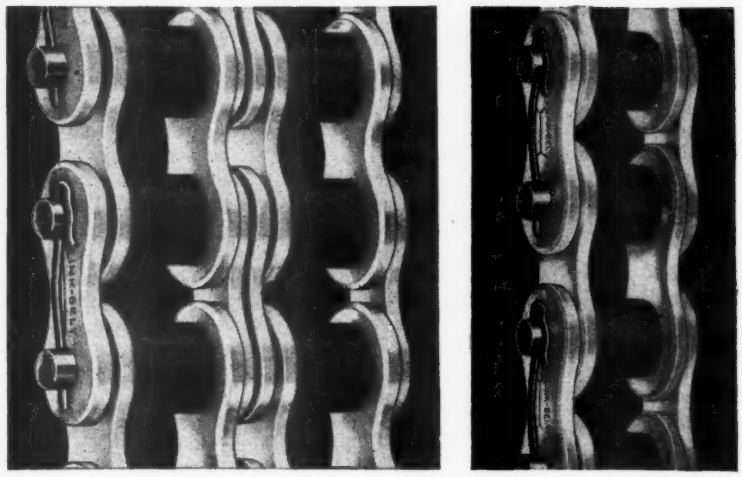

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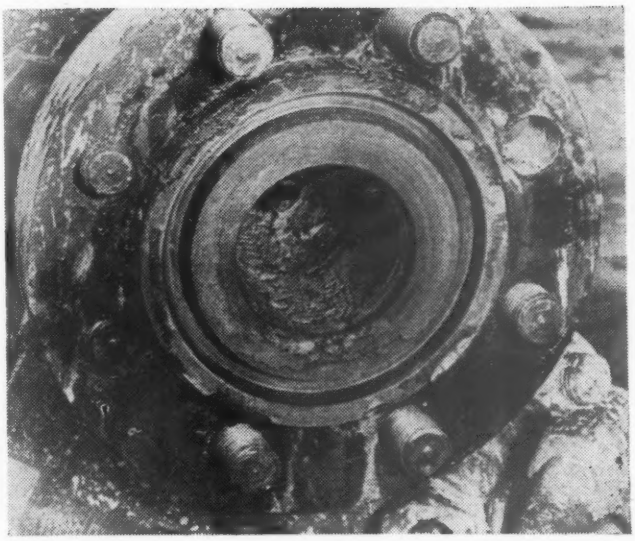

FIG. 7. Corroded ring-joint flange.

FIG. 8. Corroded ring gasket.

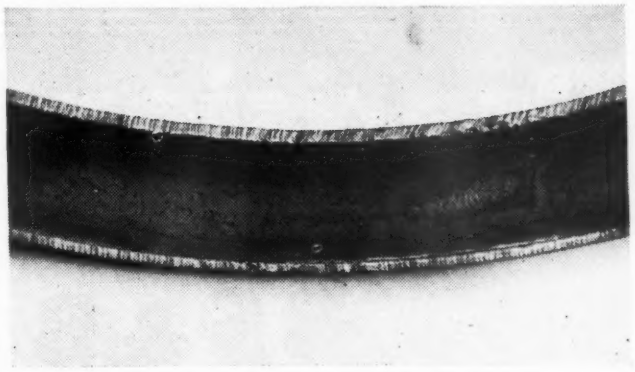

FIG. 9. Corroded pipe in gathering system.

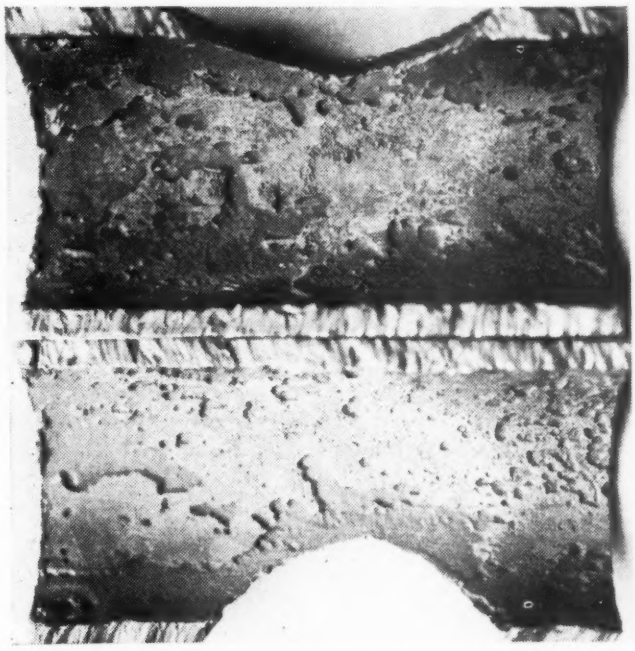

FIG. 10. Aggravated corrosion at tie-ins in gathering system.

ing the effect of the several variables involved. The iron content of waters taken at indiviual wells varies considerably, i.e., from 70 to more than 400 ppm; and, in general, the iron content appears to be lower in many wells at high rates of flow than at low rates. All evidence to date indicates that no iron or not more than a trace of iron is produced from the formation. Only one well in the field is producing more than a trace of salt water, and it has been under specific observation only a short while. The organic-acid content is fairly constant. No rate of production in any well has eliminated internal corrosion of tubing.

● **Effects of erosion.** Erosion is minor in the Katy field in comparison with corrosion. The term *erosion*, as used in this paper, includes impingement and any cavitational effects. In choke assemblies, erosion and corrosion are equally important, and frequent replacements are required. Plastic coatings are gradually removed by erosion in choke assemblies in one to two months in the average well. Erosion is a problem in only a few spots in the gathering system. The fact that erosion is a minor problem was proved by a study using metal coupons, including one made of 14-K gold, and by visual and radium inspections. Erosion does occur in piping at points of abrupt change of direction in the gathering system, particularly where lateral lines connect into main lines at right angles. The localization of corrosion on the inside of API tubing to near the down end of the joints could in a sense be connected with erosion, but is thought to be due to a reflux action or an unsteady liquid-film flow, brought about by turbulence at the couplings.

● **Stray electric currents.** A rather thorough survey was made of the flow of electric currents in the field. The magnitude and direction of flow in the gathering system was determined, and surveys were made inside of the oil-string casing in a number of wells.

It was found that an average of 1.9 amp (varied between 0.38 and 3.65 amp) was flowing into all producing wells, and that an average of 2.9 amp (varied from 0.89 to 4.96 amp) was flowing into injection wells. The difference in electric potential was measured between the top of the casing and various points in the casing in several wells. This potential varied from 0 at the surface to about 30 mv at 7000 ft with the flow line connected, and 0 to 10 mv when disconnected. The current leaves the casing from top to bottom, but a change of slope occurring in the average survey curve indicates that more than the average amount of current leaves at a depth of 3000 ft to 3500 ft.

These currents are believed to have no effect on internal corrosion; however, insulating flanges are to be installed to minimize external casing corrosion.

● **The use of chemicals to control corrosion.** Often corrosion can be effectively controlled by chemical means[5], and this is believed to be true in the case of internal corrosion at Katy; however, at the time that it was decided to try chemical control, conditions in the field made

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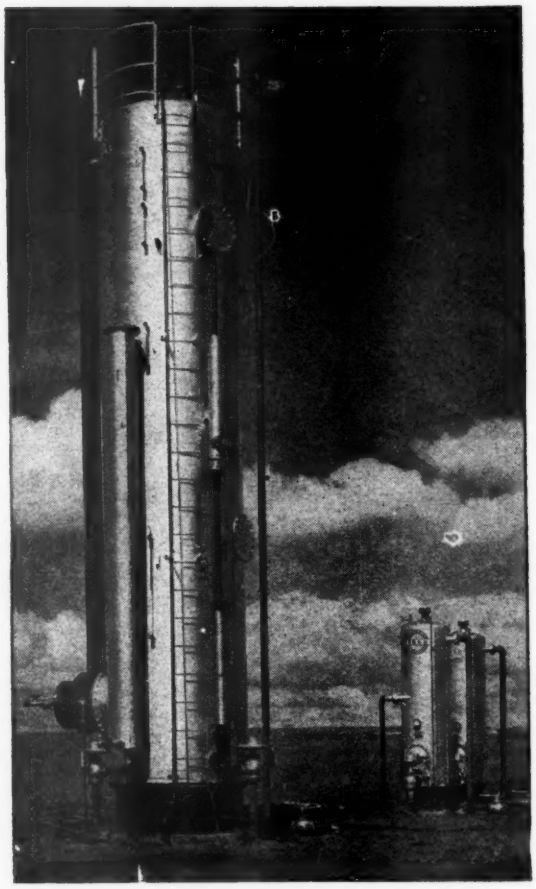

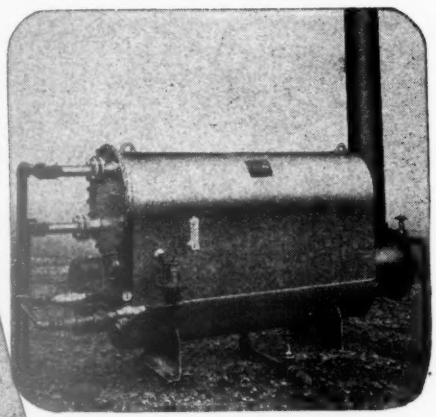

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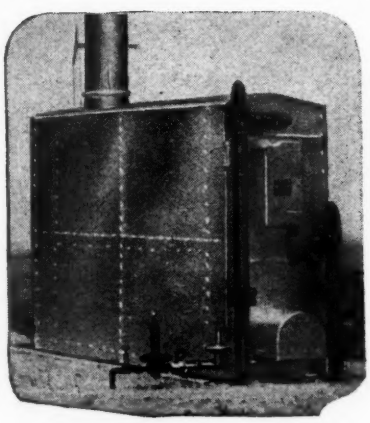

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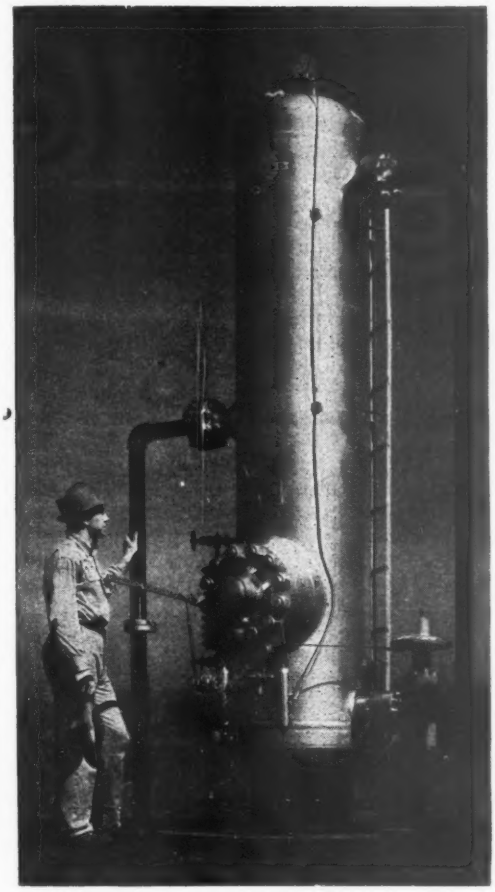

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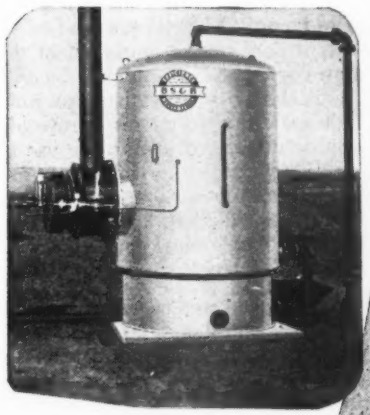

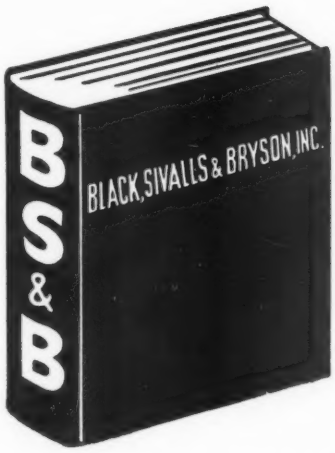

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such a procedure undesirable, if not impractical, in many wells — mainly because tubing packers had not been installed. It was believed that the producing capacity of the formation would be reduced by some of the chemicals that might be tried, or by their reaction products.

To make chemical control feasible, it is necessary that: 1, a compound having suitable chemical and physical properties be available; 2, the mechanical arrangement of the equipment be such that chemical can be injected where needed with a minimum amount of trouble, and, 3, suitable injection devices be available.

A research program has been in effect, and is being continued, in a rather intensive manner to evaluate chemicals for this purpose. Such work includes the correlation of laboratory-test results with results obtained in field trials. This program has not advanced to a satisfactory solution of the whole present problem, but it has indicated several approaches that can be used toward solution.

Laboratory tests indicated that two chemicals of the inhibitor type, viz., 1, bone oil, and, 2, carbon disulphide, warranted extensive field trials in wells not equipped with tubing packers. Field trials showed that the bone oil is 50 to 75 per cent effective as an inhibitor, but its use had to be condemned because of the odor imparted to the liquid products at the plant. The carbon disulphide was found to be only 15 to 25 per cent effective, but it does not seriously affect the plant product. The low order of effectiveness, and the possibility that the iron-sulphide scale that forms may prove objectionable in time, condemn the use of carbon disulphide. Other inhibitors are to be tested in wells without packers, but it still appears difficult to find a compound that is economical and has no undesirable characteristics.

Laboratory tests and use in other fields indicated that small amounts of neutralizing agents, such as sodium carbonate, sodium hydroxide, and ammonium hydroxide, would effectively reduce corrosion at Katy if properly injected. Soda ash was chosen, because it was easiest and safest to handle, for trial in several wells in which tubing packers were set, and tubing was perforated above the packer to allow egress of the chemical from the annulus to the tubing. After using solutions of soda ash for 90 days in several wells, it is thought that its use may prove to be an economic solution to the corrosion problem at Katy. Corrosion is being controlled with soda ash in eight wells at present (two wells have no packers). One pound of soda ash is dissolved per gallon of water, and is injected continuously into the casing at a rate of 1 gal of solution per 1 to 3 MMCF of gas per day. The pH of the treated water produced is in the range of 7.0 to 7.8, and it is believed that the pH of the water in the tubing is 6.0 to 6.5. The iron content of the water varies from 10 ppm to a trace, indicating 90 per cent or more effectiveness. No operating difficulties have developed as yet from the use of soda ash.

Chemicals useful in one field may not be useful in another. The converse is also true. Chemicals that are applicable in wells producing little or no salt water may have to be discontinued when salt-water production increases.

Any chemical injection in this work should be continuous rather than intermittent, and this has been proved at Katy. Gas-driven chemical injectors of the type commonly used in the oil fields often function erratically when injection pressures are above 2000 psi. Fig. 11 illustrates one type of newly designed pump which operates well, but further improvement in these devices appears desirable.

● **The use of plastic coatings to prevent corrosion.** Four strings of tubing lined with a baked-in plastic coating were installed at Katy during August and September of 1946 as replacements for corroded tubing. Tubing was packed off near the bottom, and mud was left in the annulus. The plastic used is that referred to as the "type 2" in the following discussion. At the time this paper was written these wells had not cleaned themselves completely of drilling mud and water, and the water analyses were considered as not being indicative of lack or presence of corrosion.

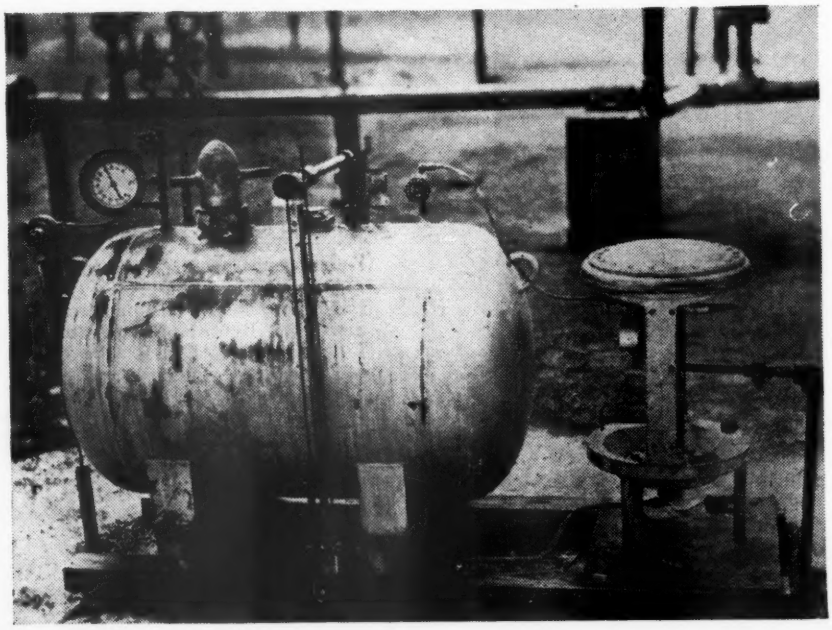
The type 2 coating was tried in wellhead and other fittings in the Katy field. Inspection after five months revealed a new condition, except in choke assemblies, where it was gradually removed by erosion in two to four months.

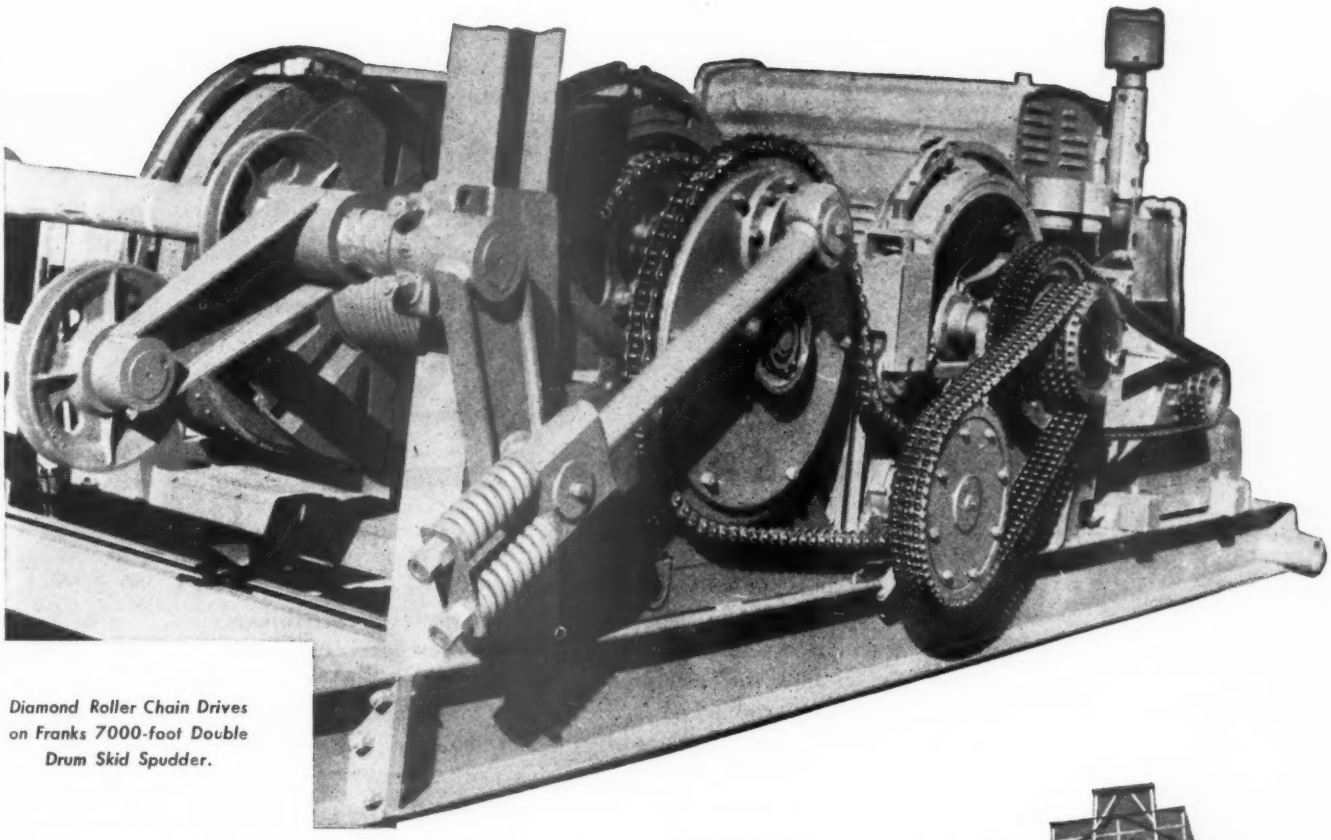
Previous work in other fields led to the trial of coatings at Katy, and it is briefly summarized herein because of probable interest.

Experiments endeavoring to perfect plastic coatings for oil-well tubing service have been carried on intensively for at least five years, but until about 18 months ago no reasonably acceptable product was marketed. All but a few of the available products were readily condemned by laboratory experiments. Most of the earlier field tests of promising coatings were made in corrosive pumping wells, but in 1945 tubing coated with baked-on, thermo-reacting, and thermo-setting plastics was installed in a number of flowing oil wells. Seven strings of coated tubing using two different coatings were installed in 11,000-ft oil wells in a Louisiana field where tubing failed in three to four years due to corrosion. The temperatures, pressures, and corrosive conditions encountered in these wells are similar to the conditions in condensate wells in the Gulf Coast region. Fig. 12 shows the condition of coated and of bare tubing in these wells, as reflected by internal caliper surveys. The charts taken in these wells are not entirely comparable because of the difference in the length of time that the tubing was in service, but corrosion of bare tubing in this field begins immediately after production starts, and the type 1 plastic was known to have begun to fail—by flaking off—after it had been in service only three months. The pitting revealed in the tubing coated with the type 1 plastic is believed to have started eight to ten months after installation. The survey of the tubing coated with the type 2 coating reveals no corrosion. Type 2 coating has a phenolformaldehyde base, is baked-on at approximately 350 F, and is applied in several layers to a total thickness of 0.005 in. to 0.006 in.

● **Arrangement of subsurface equipment to facilitate corrosion control.** Experience in the Katy and other fields[1] indicates that operators should expect corrosion in condensate wells having pressures above about 1500 psi and reservoir temperatures above 160 F if the

FIG. 11. Gas-driven chemical pump.





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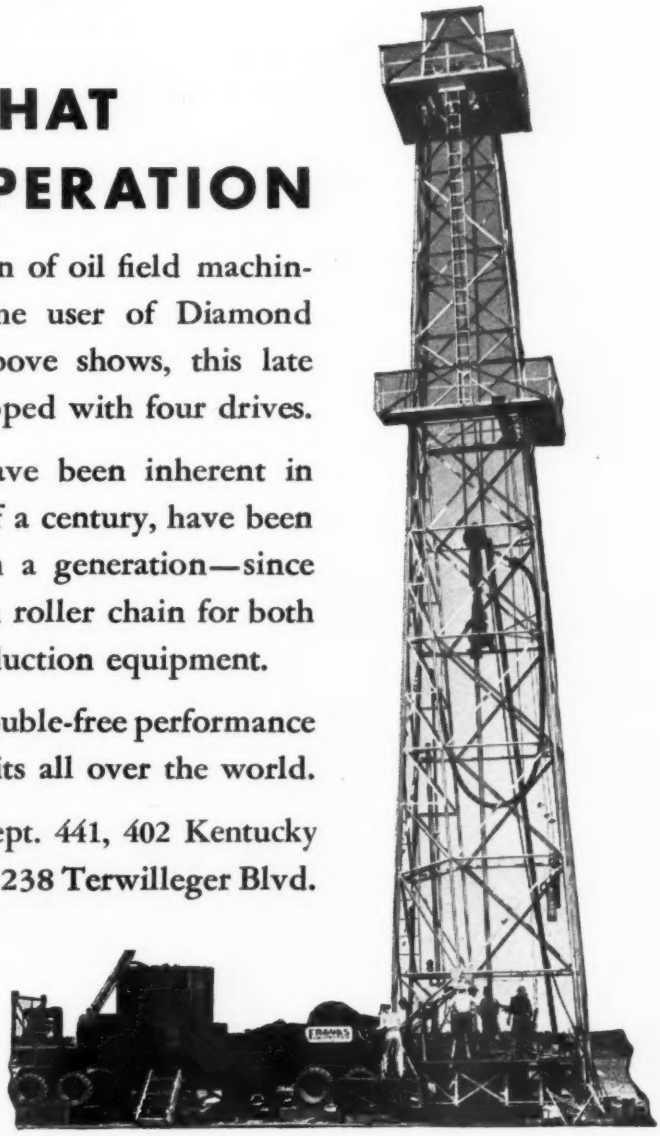

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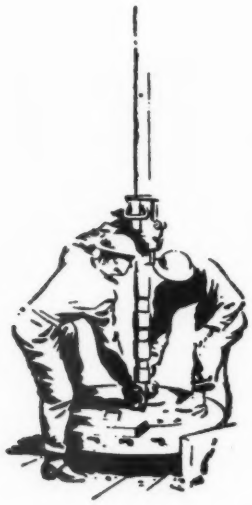

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NH-600	5 1/8 x 6	743	200 @ 2100	2600	59 x 41 x 63
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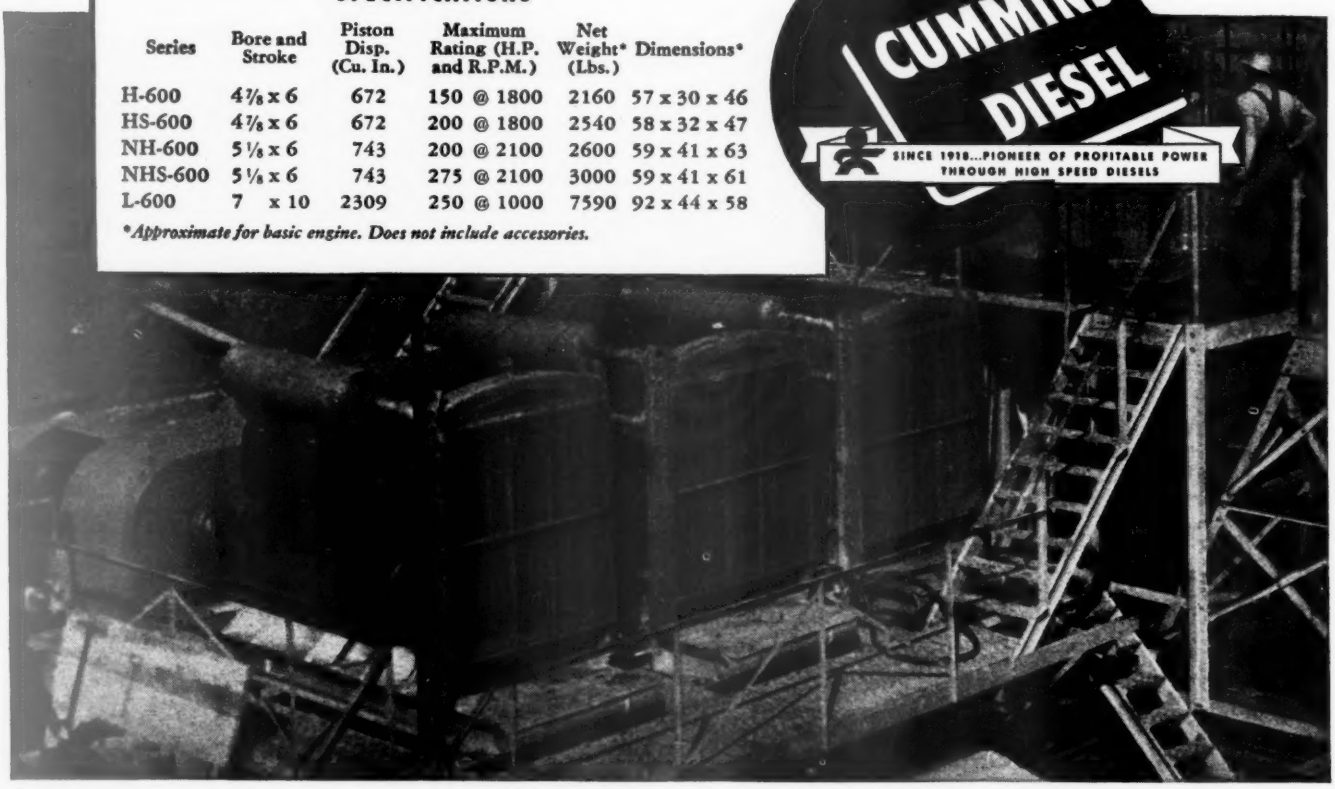

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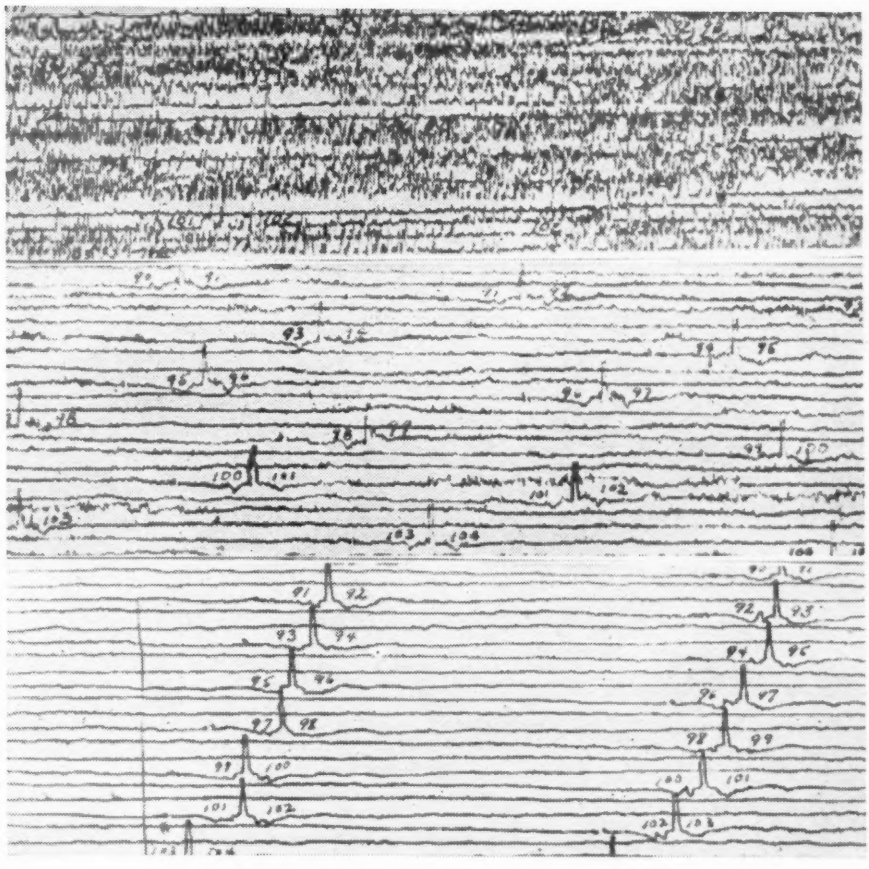
gas contains carbon dioxide in excess of 0.2 per cent by volume[6]. Previous attempts to classify wells have indicated that possibly 25 to 50 per cent of the wells in this class will encounter little or no corrosion. Present indications are that non-corrosive wells in this class are rare, and it is probable that 90 per cent are corrosive. In view of this, serious consideration should be given to completing initially and equipping wells so that control of corrosion is facilitated.

At Katy all the initial completions consisted of setting tubing, without packers, inside perforated casing. This conventional method is ideal for obtaining maximum producing capacities from tubing and casing outlets, but corrosion can attack the inside of the casing and both sides of the tubing. Chemical for corrosion control can be injected either into the tubing or casing while production is from the other outlet. Such a control depends on a perfect chemical, i.e., one that has suitable chemical and physical properties, and particularly one that will not lead to plugging of equipment or the producing formation. No highly effective chemical for this purpose has been found. As a safety precaution against otherwise undetected casing leaks, a temperature-survey program is in effect to find leaks if and when they develop.

A number of wells at Katy have been reset with tubing as large as the casing size allows. This permits: First, higher rates of production without large pressure losses, and, second, the injection of chemicals into the casing. A tubing packer is installed near the bottom to prevent chemical from going to the formation. Chemical goes through perforations installed in the tubing just above the packer. With this arrangement, the inside of the casing and the outside of the tubing are subjected to a minimum of corrosion. The principal disadvantage—as is also true when no tubing packer is used—is that, if the casing leaks due to any cause, a loss of reserves or even a wild well could result.

Tubing packers were used in the four wells that were equipped with steel tubing coated internally with plastic, and the annulus was filled with drilling mud weighing approximately 10 lb per gal. The economic success of this system, of course, depends on the life of the plastic coating, but almost complete protection against serious casing failures is obtained. If at some later time chemical has to be injected, the tubing can be perforated in place, and injection can be started, or some other means of injecting chemical might be tried.

Another system that has been considered, but has not been used at Katy, utilizes two strings of pipe installed concentrically inside the oil-string casing, complete with suitable packers. Mud would be left between the casing and the intermediate string, and chemical could be injected either into the innermost or the intermediate string while production is taken from the other. Such settings give the maximum protection against casing failures, but cost more. A rather effective inhibitor is necessary to justify the expense of the two large-diameter strings if the innermost string is used for the production tubing. If the intermediate string is as large as possible and is used as the production string, and if chemical is injected by means of a macaroni string, the hazard of fishing jobs for parted macaroni strings is a disadvantage.



Top—Bare pipe.
Middle—Type 1 plastic has failed.
Bottom—Type 2 plastic staying intact.

FIG. 12. Charts from internal caliper surveys in three oil wells indicating condition of bare and plastic-coated pipe.

In the foregoing discussion it is assumed that all tubular goods are ferrous material. All types of materials have been considered for tubing service in condensate wells and, with the exception of plastic-coated steel, no material appears to be economical—and this means glass linings, metallic linings and coatings, and alloys having adequate physical and chemical properties. Steel coated with the present semi-proven plastics costs approximately twice as much as uncoated steel. In cases when tubing fails in three to four years, such coatings can be justified if they extend the life of tubing only one year, because the cost of the replaced tubing is usually 25 to 30 per cent of the cost of the workover. The overall economics involved, insofar as tubing corrosion is concerned, is that a material costing approximately five times that of mild steels can often be justified if it will give trouble-free service for 10 to 12 years.

● **Economic aspects of corrosion control.** The estimated average annual loss due to corrosion in the Katy field is $200,000. About 75 per cent of this is for the periodic replacement of tubing, whereas the remainder is for inspecting and replacing other equipment. This estimate assumes that the casing has not been damaged sufficiently to cause early casing failures. The corrosion losses estimated previously herein would become secondary if one or more wells were to blow out and result in wild wells and loss of reserves. Also, if only a tubing-replacement program is followed in the future, i.e., no corrosion prevention is practiced—the damage resulting from frequent reworking of wells would increase the annual losses by such things as bad luck with fishing jobs, further damage to casing, and possible damage to the formation by mud and water.

Plastic coatings are not proved product, but success to date indicates that they deserve careful consideration. At Katy, for example, all the tubing in producing wells can be coated for about $140,000, or about the same amount as the estimated average annual workover expense due to tubing corrosion. Should

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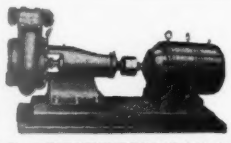

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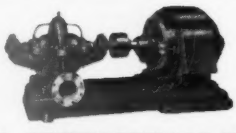

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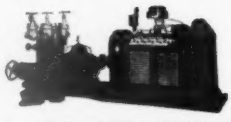

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the coatings extend the life of tubing only one year, they will pay out in comparison with using bare tubing and no corrosion protection. If plastic coatings will extend the average life of tubing five years, the use of coated pipe will probably prove to be the most satisfactory method of handling the subsurface problem. It would not solve the corrosion problem in entire wellhead assemblies because of erosion in choke assemblies, nor does it eliminate the need for probable chemical protection in the gathering system. The best advantage that plastic-coated tubing has to offer is that the tubing can be packed off to obtain protection against casing failures while a reasonable protection against corrosion is obtained. The monetary value of this safety precaution is difficult to estimate at the present time.

The successful use to date of soda ash as a neutralizing agent makes it appear to be a practical solution to most of the problems in this field. The relatively small amount of neutralizing agent required could not have been predicted from laboratory tests two years ago. It is estimated that soda ash, when used in all wells, will reduce the average annual corrosion expense to about $50,000. Its principal disadvantages are: First, the need for constant attention and checking, and, second, the fact that either the casing or an additional string of tubing is needed to convey chemical to the lower part of the tubing. The chemical itself will cost about $8000, whereas the remainder is chargeable to: 1, expense of applying; 2, checking results obtained, and, 3, losses not prevented. Some type of chemical treatment appears desirable in the gathering system, and the soda ash injected for subsurface protection also fills this need.

Other more expensive chemicals may prove as economical as soda ash—particularly if they are found and applied in those wells that at present are scheduled for workover jobs so as to postpone or eliminate those workovers.

The amount of future corrosion losses cannot be estimated too accurately because of lack of complete knowledge of the condition of casing in the wells, and because the change to the program of producing only through the tubing will alter the corrosion rate in the tubing, well heads, and gathering system. It is believed that some casing failures will occur in the next few years. This will require the installation of liners in affected wells, and will result in reduced flow capacities. Some additional wells will be required, the cost of which will be chargeable to corrosion. The higher rate of flow through tubing will probably increase tubing corrosion. The lowering of the pressure in the gathering system, amounting to about 325 psi, will probably reduce the corrosion in the wellheads and gathering system, so that it will become a minor problem or it will reduce the amount of chemical required to prevent corrosion.

● **Conclusion.** Corrosion encountered at Katy is typical of that found in many condensate fields. Experience in that field will aid in minimizing corrosion losses in other fields.

Two methods of preventing corrosion, viz., 1, use of plastic-coated steel and, 2, use of neutralizing agent, appear to be useful for reducing the corrosion expense at Katy. The chemicals tried as inhibitors have not been satisfactory. Other chemicals are being tried in individual wells.

Research work has aided materially as a background for full-scale field experiments. Considerably more research is required to obtain a better understanding of phenomena observed in the field. Continued research is needed to cope with continuously changing conditions in condensate fields and to correlate more closely field tests with laboratory tests.

Continued support should be given to the NACE high-pressure well-corrosion committee in an effort to hasten the systematic testing of alloys in condensate-well service.

Operators should expect corrosion in condensate fields, and should take corrosion into account when developing new fields or when reworking old fields.

Inspections made early in the life of a field would result in equipping wells so that corrosion control is facilitated, and will reduce corrosion losses. The newer tools—such as caliper surveys and radium inspections—allow rapid, accurate determinations to supplement visual inspections and water analyses.

In fields where corrosion is found, early field trials of promising methods should be made rather than waiting until all of the questions are answered by laboratory studies.

Keeping equipment in a safe operating condition is considered more important than the monetary losses due to corrosion in condensate fields.

● **Acknowledgment.** The author wishes to acknowledge that a large portion of the work done in connection with the problem at Katy was performed by the personnel of the Gas Division and the Production Research Division, Humble Oil and Refining Company. The many previous papers and reports pertaining to condensate corrosion have been helpful in the preparation of this paper.

The kind permission of the Humble Oil and Refining Company to publish this paper is appreciated.

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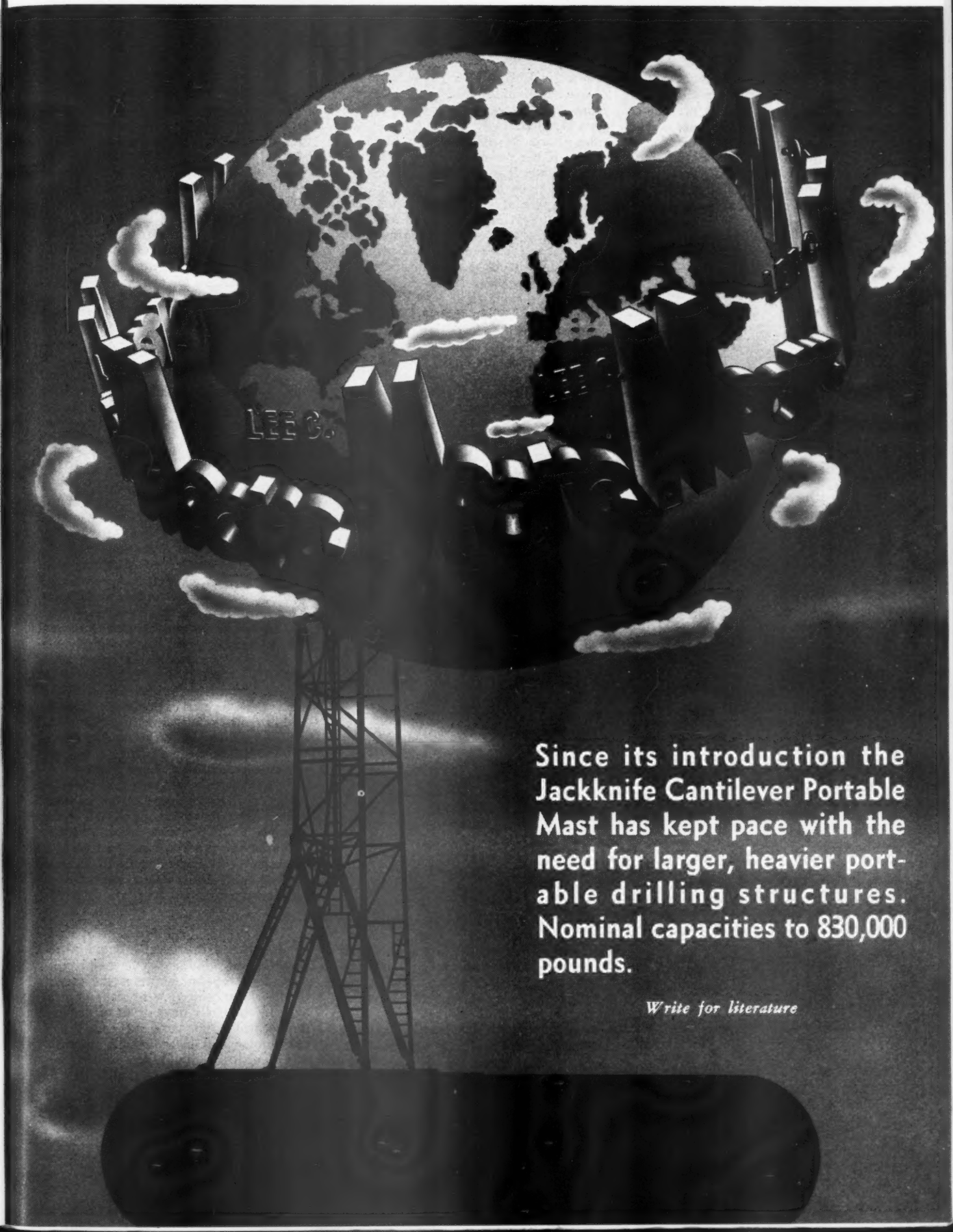

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Use of explosives in secondary recovery*

By R. C. EARLOUGHER, Earlougher Engineering

● **Abstract.** This paper discusses the use of shooting in producing and injection wells in water-flooding programs. Although the oil sand in all wells is shot in the majority of operations, some floods have been developed without shooting, and are apparently obtaining successful results. The question of whether the sand should be shot is probably dependent upon the sand structure and characteristics in individual fields or areas.

In almost all secondary-recovery developments where oil production is obtained from sandstone formations, it is common practice to shoot the pay strata in both the injection and production wells. This practice has followed procedure used in the early days of the industry when it was found that most new wells would produce oil at higher rates after being shot with nitroglycerin. It is believed that the effect of the shot is not only to clean the sand face in the well bore but also to cause radial fractures from the well into the sand body and thus permit a more rapid flow of fluid from the sandstone into the well or of water into the formation, whichever the case might be. Field data and numerous tests substantiate the fact that, in cases where shooting does greatly increase the productivity of a producer or the injectivity of an input well, the result obtained must be by way of radial fractures, and not by increase of hole size alone. In effect, however, these fractures appear to give the same result as an increase in hole diameter to as much as 50 ft.

It must be recognized that even now very little is known of what actually happens at the bottom of a well when a shot goes off. It is known, however, that in most cases in a water-flooding development it is desirable and advantageous to shoot both the input and output wells in order to obtain satisfactory water-injection and oil-production rates. Numerous field tests in the Bradford field and the shallow fields of northeastern Oklahoma and eastern Kansas have shown that good injection rates can be obtained by shooting, whereas without shooting the rates will be very low, and certainly far too slow for economic flooding. At the same time it can be said that the need for shooting and the size of the shot may depend on any one or all of the following: Permeability, depth, and characteristics of the sandstone itself.

If permeability of the sand is low as in Bradford, shooting—and heavy shooting at that—is necessary. Even though the depth is sufficient to permit surface injection pressures of as high as 1500 psi to 2000 psi, the sand is so tight (average 5 to 10 millidarcys) that, even with shot concentrations of as high as 5 qt per ft, satisfactory injection rates cannot always be obtained. On the other hand, if the permeability were a great deal higher, it is probable that shooting would not be necessary other than for the purpose of selective shooting. This latter operation consists of shooting heavily the sand of lowest permeability and that of higher or highest permeability lighter, or not at all, in order to even the water-front travel from the well into the vertical sand section. At the present time water flooding is being carried on in some localities—especially North Central Texas, where shooting of even shallow sands is not employed because of the fact that the permeability is so high (500 to 2000 millidarcys)—that inputs will take sufficient volumes of water without shooting. Neither is selective shooting adaptable in many such cases because of the extremely thin sand sections and non-uniformity of high and low permeability in the vertical section.

Selective shooting based on individual well cores has now been in use on a rather wide scale by many operators for six to eight years. In most cases where it has been used, it has proved advantageous in increasing economic oil recovery and at the same time reducing overall "water-injection to produced-oil" ratios. Increase in oil recovery, of course, results in increased gross income, whereas reduction in injected-water to produced-oil ratios results in reduced operating costs. Unfortunately it is not possible to develop the same property and same wells first with conventional shooting and then do it over again using selective shooting in order to get a direct comparison of the two methods. However, by comparing adjacent leases—one developed in the conventional manner without selective shooting, and the second with selective shooting—it has been possible to obtain fairly reliable conclusions that this type of shooting can result in reduced water-oil ratios, increased injection rates in wells having abnormally tight sand and, in turn, increased economic oil recoveries. In planning a selective shot, however, the factor of oil and water saturation must be considered in addition to permeability. This is especially true in old fields where there are a number of old abandoned wells, any one of which may have been a leaker resulting in accidental water drives in certain areas under a lease.

The effect of a shot in different wells apparently depends to a large extent upon the physical characteristics of the sandstone itself. This might best be exemplified by comparison between shooting in the Bradford area of Pennsylvania and in the shallow-sand area of northeastern Oklahoma and eastern Kansas. The Bradford sand is very hard, tight, and dense; whereas the Bartlesville sand in the shallow fields of the Mid-Continent is somewhat coarser and a little softer. Apparently, as a result of this difference, shot concentrations in the Mid-Continent of about twice the size used in Bradford are necessary in order to obtain the same increase in water-injection rates. For example, a sand in Bradford having an average permeability of 10 millidarcys might be shot using a concentration of 2.5 qt of glycerin per ft to obtain a fivefold increase in injection rate; whereas a sand of the same permeability in eastern Kansas would require a concentration of 4 qt per ft to obtain a similar increase. Likewise, it has been found that some of the deeper Bartlesville sand in the Mid-Continent will take little more water after shot than without shot, especially in areas where the sand is cleaner, with smaller amounts of shale in the cementing material—and, although quite hard, at the same time of a crumbly nature. One operator[1] in southeastern Kansas, flooding Bartlesville sand at a depth of approximately 1000 ft, reports that injection wells not shot seem to take water as readily under 800 psi surface pump pressure as those wells that were shot. Similar results have been reported from east central Kansas where Bartlesville sand is being flooded at depths varying from 1800 ft to 2800 ft. There are two possible explanations for these results. The first is that, because of the greater depths, higher bottom-hole injection pressures can be used to obtain the desired injection rate. The second is that it may be the sandstone in these cases shatters and crumbles when shot, rather than fracturing radially outward from the well bore. In by far the majority of cases, however, in the more shallow flooding operations in the Mid-Continent area, it has been rather amply proved that shooting is not only desirable, but necessary, if satisfactory injection rates are to be obtained.

There has also long been a great argument between the use of liquid nitroglycerin and solidified. The majority of water-flood operators prefer the use of liquid—largely in view of their experience in the early days of flush production, at which time most of them were of the opinion that better results were obtained with the liquid. Again, however, there are those who claim that just as satisfactory results, or even better, can be obtained with solidified. The correct

*Paper presented to Division of Production, Twenty-sixth Annual Meeting of the American Petroleum Institute, Chicago, Illinois, November 12, 1946.

[1]Marion H. Sekol, Tulsa, Oklahoma, personal sonal communication.

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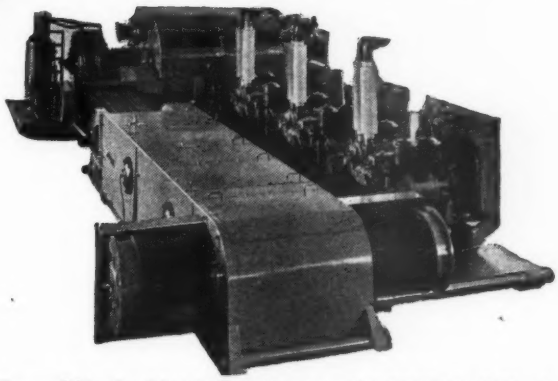

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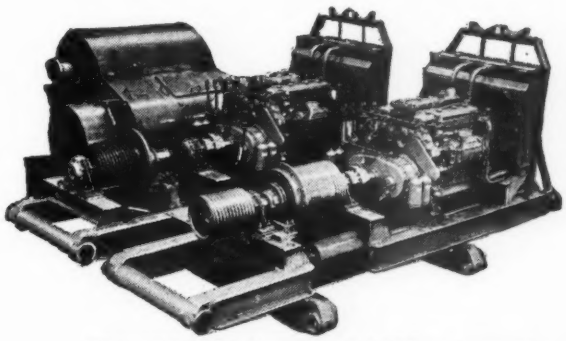

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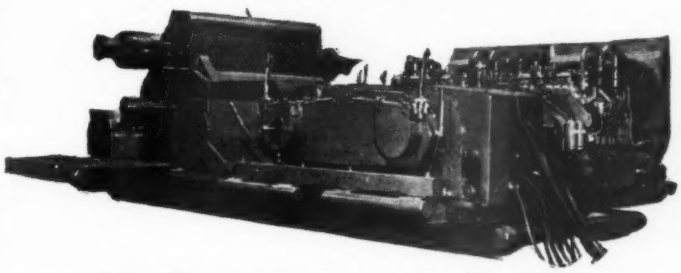

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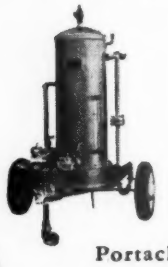

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answer probably still remains to be found.

Numerous operators have made different tests in trying to prove to their own satisfaction which is the best shooting medium. In most cases, however, results seem to come out in favor of the medium that the operator himself most preferred. In other words, advocates of solidified nitroglycerin have proved to their own satisfaction that it does as good a job, or better, than the liquid; whereas the advocates of liquid have obtained results that satisfy them that their choice is preferable. Again, however, it is believed that the use of one or the other may depend largely upon physical characteristics of the sand formation in question. For example, an operator[2] in southeastern Kansas, who had used solidified nitroglycerin for a number of years, finally began using liquid. He has reported that, after that change had been made, clean-out time and quantity of sand cleaned from the shot hole was reduced very materially and at the same time higher injection rates in the input wells resulted. Another operator in northeastern Oklahoma, who had been a strong advocate of solidified began developing a lease where the sand was quite tight and hard and, after completion of two injection wells, found that neither of them would take appreciable quantities of water. Consequently, the next few wells drilled were shot with liquid, and were found to take considerably greater quantities of water under the same existing surface pump pressure. These results were sufficient evidence for these operators that their neighbors had been right, and that liquid glycerin in these cases is preferable to solidfied—although the cost is greater. In another field in the Mid-Continent, on the other hand, an operator found that wells shot with liquid nitroglycerin required much greater clean-out time than those shot with solidified nitroglycerin.

● **Conclusion.** In conclusion, it is apparent that too little is actually known regarding the action and effect of shots, in either injection or production wells, other than the fact that in a large number of cases either production or injection rates can be materially increased by shooting. Beyond that, most conclusions are based primarily on theory, with too little factual data to prove or disprove the theory. Without question, however, there are fields or areas in which shooting of the sand sections in the wells is absolutely necessary if best results are to be obtained; on the other hand, there are also other fields or areas where it appears that little benefit is to be gained by shooting. For those sands that do respond favorably to shooting, with resulting increases in injectivity or productivity rates, it is believed that flooding efficiencies can be increased by the use of selective or varied shots, dependent upon variations in permeability and oil and water saturation.

[2]R. O. Bankson, Pittsburg, Kans., personal communication. ★ ★ ★

Use of plastics in consolidating loose sands in wells*

By R. H. SMITH and A. C. POLK, JR., Dowell Incorporated

● **Abstract.** The physical properties of the materials are listed, together with a short explanation of how this material binds the sand grains together without materially reducing the effective permeability of the sand. The chemical can be used in wells with bottom hole temperatures ranging from 105 F to more than 350 F. A description of the equipment required and the techniques used for applying these plastics to the wells is included.

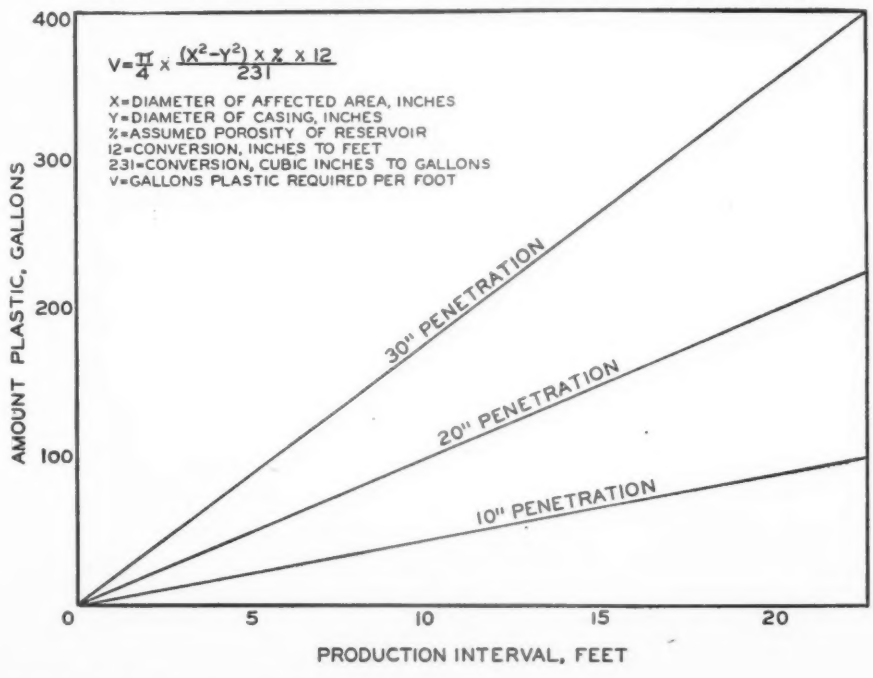
● **Introduction.** Recovering oil and gas from unconsolidated sand formations offers one of the most troublesome of all production problems. These sands generally present no particular trouble while drilling is in progress, but after the well has been completed and a pressure differential has been established across the face of the producing zone, the formation begins to "slough" resulting in "sanding up" of the well. The term "sanding up" refers to that condition where sufficient volumes of sand have moved into the well bore or casing to cause a serious reduction or complete halt of all flow of oil, water or gas. In rare cases a well may produce only a small amount of sand and still continue to flow or pump with the sand being carried to the surface in the fluid stream. However, in such instances, a costly repair bill may be the result, due to the cutting action of the sand on surface and pumping equipment.

The difficulty of producing petroleum from sands that are loosely cemented long has been recognized by petroleum engineers but only within the last few years has any new approach to the problem been undertaken. This involves the use of plastics that are capable of bonding the individual sand grains in place without materially reducing the effective permeability of a formation. The successful application of plastics for the consolidation of poorly cemented sands is relatively recent but it now is being widely used in many of the more difficult areas on the Gulf Coast of Texas and Louisiana.

This relatively new use of plastics[1] in the oil fields has been preceded by much laboratory and field research on the use of various chemicals[2,3] for solving numerous well completion and work-over problems. Plastics now are being used successfully to control gas-oil and water-oil ratios,[4,5] in zone isolation, the repair of casing leaks, the elimination of caving in cable tool drilling wells[6,7], and in the setting of liners[8] and casing.[9] Sand consolidating plastics are, however, basically different from all others in that they must not form an impervious seal.

*Presented before American Institute of Mining and Metallurgical Engineers, Galveston, Texas, October 3-5, 1946. Published in *AIME Petroleum Technology*, March, 1947.

FIG. 1. Assuming a porosity of 30 per cent, these curves indicate plastic gallonage requirements for a well with a 7-in. casing. All volumes on the curves are "V" plus the casing volume of the affected section.



● **Field practices.** In the past the approach to the "sanding up" problem usually has been the mechanical obstruction of the movement of the sand grains; however, all such methods are limited in that the sand movement is stopped, not at its source, but at the bore of the well. And, such methods must rely on the use of various types of screens and gravel packing.

Although the setting of screens has become a widely accepted practice, it does not always provide the final answer to the problem. The best of screens may have to be pulled in order to clean them of corrosion products, silt, and other foreign materials that lodge in the openings. Then, too, screens do not always stop the movement of the sand but oftentimes serve merely to retard it with the result that they are ultimately "cut out." When this occurs an expensive reworking of the well usually follows.

Some operators have improved the situation by gravel packing a screen in place. This method has proved satisfactory in a large number of wells, but it can be a very costly procedure, and, similar to other screen settings, it merely relies on the holding back of the sand. In the event a gravel packed screen is cut out by sand, and they frequently are, the result is a rather complicated, expensive work-over operation. Less commonly used, but often effective, is a hydropacked or prepacked screen that is set inside perforated casing across the producing interval. This method generally is effective for holding back the sand, but in many instances it retards the oil or gas production to the extent that the well fails to be an economic producer.

Wells that are completed in the more consolidated sands seldom offer any particular difficulties due to sanding up until they begin to produce water. The movement of the water through these sands dissolves the cementing materials that were originally in place, thereby allowing the movement of the sand grains proper, which finally results in the well's sanding up. When water makes its appearance in a well, more fluids must be produced in order to obtain the daily allowable. This increased production creates higher fluid velocities through the sand grains, and rapid destruction of the screens. Once such a condition exists, an operator may find it uneconomical to continue setting screens and cleaning out, resulting in the early abandonment of the well.

● **Properties of plastics.** The basic prerequisites for plastics that can be used in wells for the consolidation of loose sands are that they must penetrate the sand at low pressures, possess adequate compressive and tensile strength in a

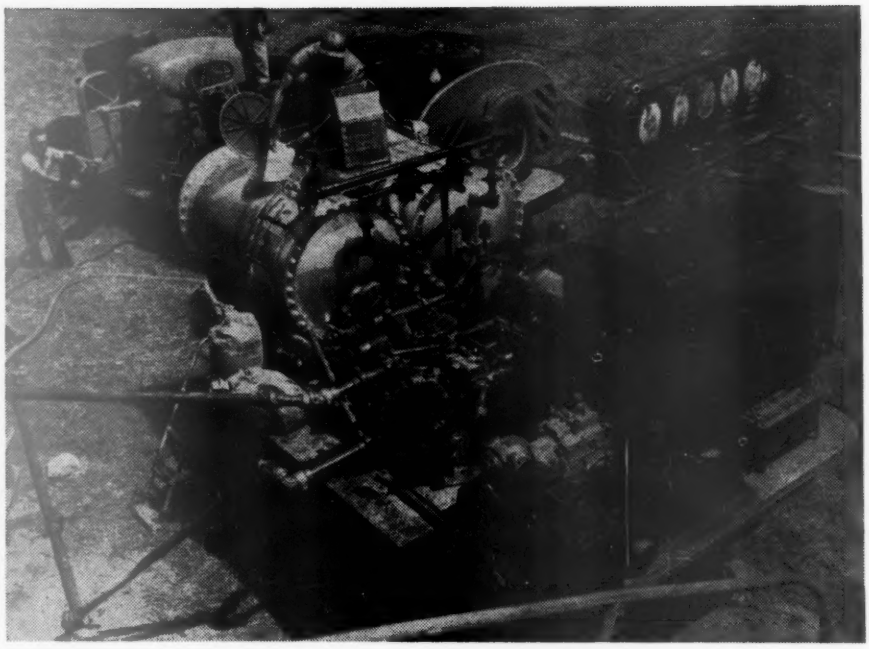


FIG. 2. This picture, taken at a well near Houston, shows the pump truck with proportioning and plastic transporting tanks. The trailer carries motor-driven plastic mixers and plastic pump.

solid state, and, when solidified, exhibit inherent permeability.

There are many plastics forming liquids available that are mobile at ordinary temperatures and are of such a nature that of themselves they spontaneously undergo polymerization, condensation, or association reactions until the whole liquid becomes an insoluble, strong, solid plastic. The liquid plastics are fairly stable at ordinary temperatures, but when properly treated or subjected to the temperatures encountered in oil wells, the rate of polymerization, condensation, or association is increased, resulting in the liquid becoming a solid in a relatively short time. The time required for the liquid plastic to make the transition from a liquid to a solid state depends, among other factors, upon the nature of the plastic and the temperature to which it is subjected.

The plastic materials used in sand consolidation are true fluids with chemical and physical properties similar to those exhibited by the plastics used in other oil well remedial work. However, the sand consolidating materials are unique in that when changing from a fluid to a solid state they become more dense. This decrease in volume results in the development of permeability within the plastic filled pores of the sand body. The plastic is chemically inert under the conditions found in wells, has a specific gravity of 0.96, a viscosity of approximately 1.5 centapoises, and a surface tension of 36 dynes. It is thermo-setting and can be successfully applied to wells whose bottom hole temperatures range from 105 F to 350 F. The compressive and tensile strength of this plastic material compares favorably with that of the ones used in other oilwell remedial work.

● **Effect on permeability.** Numerous studies made in the laboratory in an effort to plug a consolidated sand core with these plastic materials resulted in a permeability reduction in the order of only 50 to 70 per cent; however, most of the producing sands to which these plastics have been applied often exhibit permeabilities as high as 2 darcys, in which a reduction in permeability of as much as 70 per cent would be of no particular consequence. Actual field production data obtained from wells where friable producing formations have been consolidated with plastic show that the effective permeability usually is reduced by no more than 10 to 15 per cent.

As the mechanism of sand consolidation through the use of plastics relies upon a bonding of the individual sand grains in the formation, with a related loss in permeability, the type of well to which this service is applicable clearly is indicated. Usually it may be assumed that any formation that has a combination of an effective reservoir drive plus a high permeability may be successfully consolidated; but, as these two factors are decreased the possibility of reducing the effective permeability of the formation beyond the economic limit is increased.

TABLE 1

State	Pool	Producing horizon	Bottom hole temp., F	Producing interval, ft	Plastic used, gal	Maximum injection pressure, psi	Remarks
Texas	Withers	Erie	150	5522-5524	105	600	New zone completion. No sand movement following plastic.
Texas	Picket Ridge	Marginulina	132	4690-4692	75	2200	Completed with screen, pumping. Following plastic, natural flow.
Louisiana	Erath	Miocene	165	7731-7744	250	2000	Producing 4 per cent sand prior to treatment. No sand following treatment.
Texas	S. Cotton Lake	Frio	156	6480-6483	150	1400	Well sanded up and abandoned. Following plastic, produced on natural flow.
Texas	Cedar Point	Miocene	135	4250-4254	150	2500	New zone completion. No sand trouble following plastic.
Louisiana	N. Crowley	Miocene	150	4822-4836	250	1000	Producing sand prior to treatment. Pipe line oil following plastic.
Louisiana	Leeville	Miocene	180	7770-7805	330	2400	Screen sanded up. Now flowing through casing perforations.
Texas	Thompsons	Frio	140	5385-5391	150	1075	Originally completed with screen. Following treatment, producing through casing perforations, no sand.
Texas	Lefever	Cole	110	1759-1763	150	200	Sanded up. After treatment, pumping 40 bbl per day.
Louisiana	Delta Farms	Frio	160	6929-6932	110	1500	No sand troubles following plastic application.
Texas	Wade City	McNeil	160	4890-4906	100	1000	Producing sand before treatment, pipe line oil after.
Texas	Barbers Hill	Oligocene	145	4055-4085	225	1250	Producing pipe line oil, natural flow, following treatment.
Texas	Pierce Jct.	Frio	145	4708-4730	100	1000	Following treatment, producing 91 bbl daily, no sand.
Texas	Barbers Hill	Oligocene	135	4055-4085	222	1200	144 bbl daily production with no sand difficulties, following plastic.
Texas	Barbers Hill	Oligocene	112	4260-4290	200	1250	Producing 155 bbl daily following treatment, no sand.
Texas	Freer	Cole	107	1722-1726	100	200	60 bbl per day pumping, no sand trouble following plastic.

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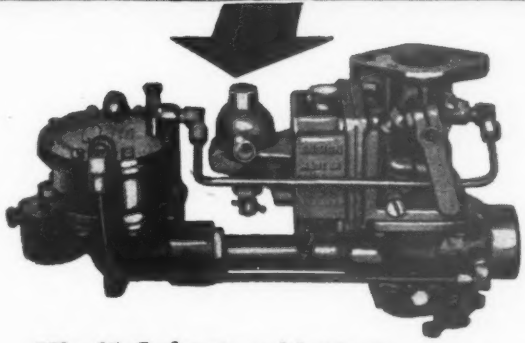

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● **Basic prerequisites.** Although the foregoing considerations are of primary importance, there are various other factors that play an important part in the successful application of sand consolidating plastics. Among these are bottom hole pressure and temperature, water-oil and gas-oil ratios, type of reservoir control, producing status, size of hole, production history, and type of completion. An analysis of these items will determine the technique of application, the volume of material required and, to some degree, predict the ultimate result. Due to the inherent chemical properties of the plastics suitable catalysts are required to control their setting time, the selection and amount of which is determined by the bottom hole temperature of the well. If follows, therefore, that fairly accurate bottom hole temperature determinations must be made. The bottom hole temperature range for the plastics and catalysts now available is from 105 F to more than 350 F.

When wells that have produced large quantities of sand are considered for treatment it is highly important that the producing interval be squeezed with a material that will lend competence to the formation immediately adjacent to the well bore or casing. Such operation is required because it is believed that, in wells of this type, the formation in the critical area is in a semi-fluid state, and, before sand consolidation plastic can be applied successfully, the formation in the area near the well bore must be treated with a material that will give it the required rigidity. Following this step, the reinforced sand may be gun perforated over the desired interval and the sand consolidating plastic applied to the formation through the gun perforations. Another fundamental requisite for the success of any sand consolidating application is the absolute isolation of the affected zone. The lack of a proper bond between the casing and the formation will permit the fluid plastic to travel along the side of the pipe rather than to flow laterally into the desired producing formation. In order to emphasize these two basic requisites, each of which are dependent upon well conditions, it should be noted that in every instance where this procedure has been followed, the sand consolidation with plastic has been successful.

There is an idea generally prevalent that if a sand sloughs, moves into a well and is actually produced with the fluid, a cavity is created adjacent to the well bore that is proportionate in size to the volume of sand removed. If this were true it would follow that large volumes of plastic would be required to consolidate the sand in a given production interval. Experience has shown, however, that if a sand, whether oil productive or not, lacks sufficient bonding material to make it competent under normal producing conditions, then it is noncompetent throughout the entire reservoir. Consequently, when a sand adjacent to a well is produced it follows that more sand moves in to fill the vacated space, in a fashion similar to the movement of a fluid. Field data indicate that these so-called "cavities" do not exist. This is proved essentially by the fact that abnormal quantities of materials are not required to consolidate effectively a given productive interval. It is true, therefore, that even though a considerable quantity of sand has been removed, effective consolidation of the formation can be obtained.

The amount of sand consolidation plastic required for any job can be calculated readily if the diameter of the well bore, the desired depth of plastic penetration, the average porosity, and the thickness of the producing section are known. The formula for making such calculations is given in Fig. 1 along with data on the amount of plastic required for 10, 20, and 30 in. penetration over production intervals from 0 to 25 ft.

● **Methods of application.** In wells where the casing has been set and cemented in place on top of the sand, with a screen set through the sand, the customary practice is either to remove or to gun perforate the screen before applying the plastic.

The actual operation of injecting sand consolidation plastic into a formation is accomplished by the squeeze technique.[10]

In this method certain procedures are used to obtain uniform distribution of

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the plastic across the completion interval. These include a special plug landing tool to control the placing of the plastic, a drillable or retrievable retainer to accomplish the "squeeze," and a predetermined length of perforated plastic or drillable metal tailpipe below the retainer. The tailpipe is used below the retainer to insure even distribution of the injected fluid over the completion interval.

After this assembly is in place in the well, oil is pumped into the tubing in sufficient volume to displace the mud or other fluids from the tubing and from the casing, below the retainer. The retainer then is set and a feeding rate into the formation is established with oil. This is followed by the squeezing of the plastic into the formation. After the required setting time of the plastic has elapsed the remaining plastic plug is drilled out, usually with a rock bit on a string of tubing, and the well is put on production.

If a retrievable retainer is used it is set well above the perforated section to assure its removal following completion of the plastic application. Where a drillable retainer is used the tubing is backed-off and pulled from the well and both the retainer and tail pipe are drilled out at the same time as the hardened plastic plug.

The surface equipment that is used in this work has been designed and built especially for the preparation and application of the various plastics to wells.

A large tandem drive truck carrying a motor-driven high pressure, high volume pump, also proportioning and plastic tanks, is used in conjunction with a large four-wheel trailer on which is mounted two 300-gal motor-driven plastic mixers and a specially designed triplex plastic pump. This type of equipment is illustrated in Fig. 2.

The triplex pump on the truck is used for circulating, determining formation injection rates, displacing the plastic from the tubing, and squeezing it into the formation. The mixers are required for necessary, thorough blending of the plastic and catalysts. The pump on the trailer unit is used to discharge the finished plastic from the mixers into the tubing.

● **Summary of results.** Since the introduction of the service over 150 wells have been given treatments with this type of plastic. Generally speaking, the results obtained have been encouraging and, in the main, quite succesful. It is estimated that more than 80 per cent of all the treatments made to date are successful.

Table 1 contains pertinent data on 16 wells, typical of the results obtained in recent months. The wells cover a wide range of formations, temperatures, depths, and thicknesses of producing intervals. The temperatures vary between 110 F and 180 F with an average of 150 F; the thickness of the producing intervals range from 2 ft to 60 ft, with the average 15.5 ft; the plastic gallonage averages 165 gal per well, with the maximum being 330 gal and the minimum 75 gal.

Most of the treatments to date have been made on wells where the producing zones did not exceed 5000 ft in depth, although some sands have been consolidated at depths less than 2000 ft and others at depths exceeding 9000 ft. The pressures required to inject the plastic into these sands have not been high when compared to those pressures that frequently are encountered in squeeze cementing. Referring again to the table, the highest pressure encountered in this group of wells was 2500 psi, with the average for the tabulation being 1325 psi.

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Isomerization of light hydrocarbons*

By STEPHEN F. PERRY, Standard Oil Development Company

● **Abstract.** This paper describes processes for the conversion of normal butane to isobutane and of normal pentane to isopentane, which were developed cooperatively by the Anglo-Iranian Oil Company and the Standard Oil Development Company. The essential features of both processes include: (1) the use of a highly selective solid catalyst, namely, $AlCl_3$ adsorbed on bauxite, and (2) a technique for maintaining the activity of the catalyst by the introduction of fresh $AlCl_3$ along with the feed.

Butane isomerization plants utilizing the process described in this paper have been built in sizes ranging from 600 to 3600 bbl of isobutane per day, the combined capacity amounting to about 25,000 bbl per day. A typical plant is described in detail. Several of the plants were constructed almost entirely from existing equipment, with a substantial saving in time and critical materials, when the war time need for isobutane was most pressing. Plant performance data and the major operating difficulties encountered and overcome are discussed.

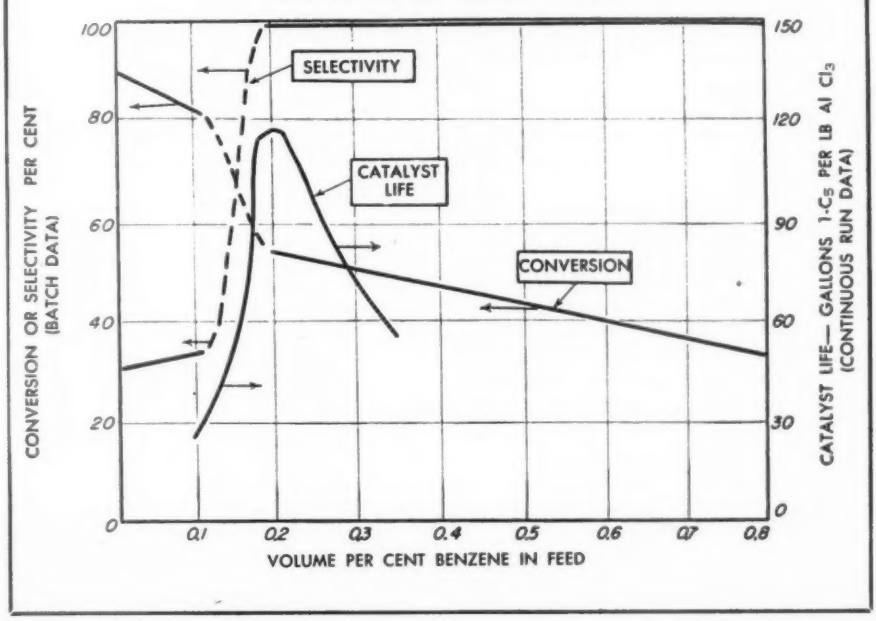
In general, paraffins of branched-chain structure have better anti-knock properties than the corresponding straight-chain or normal paraffins and are superior fuels for use in internal-combustion engines. The trend toward more efficient, high compression engines that require higher octane fuels has placed a premium on the production of branched chain or isoparaffins. This paper describes catalytic processes for the conversion of normal butane to isobutane and of normal pentane to isopentane, which were developed cooperatively by the Anglo-Iranian Oil Company and the Standard Oil Development Company. Isopentane is an excellent gasoline component, having an octane rating of 90 (ASTM motor method) as compared with 62 for normal pentane; isobutane, although of limited value as such due to its high volatility, is required in the alkylation process for the manufacture of highly branched paraffins of higher molecular weight (C_6-C_9) for aviation fuel. The butane isomerization process has been applied on a large scale and commercial operations are discussed.

● **Process development.** It had been known for some years that aluminum chloride was capable of catalyzing the conversion of normal or straight-chain paraffins to branched paraffins. This catalyst also initiates cracking and polymerization, however, and in contact with hydrocarbons under isomerization conditions may be converted from a granular solid into a liquid $AlCl_3$-hydrocarbon complex or sludge that is highly corrosive to steel equipment. Other properties of $AlCl_3$ that appeared to be unfavorable for the development of an operable isomerization process are (1) its appreciable solubility in liquid hydrocarbons and (2) its appreciable vapor-pressure even at temperatures considerably below its sublimation point. These properties would result normally in the loss of catalyst from the reactor and its accumulation in subsequent processing equipment with deleterious effects. The object of the development work was to overcome or avoid these difficulties and thus to obtain an operable continuous process.

Butane isomerization. The first commercial plant for the conversion of normal butane to isobutane was one that was designed by engineers of the Standard Oil Development Company, and placed in operation by the Nederlandsche Koloniale Petroleum Maatschappij (a subsidiary of the Standard-Vacuum Oil Company) in their Palembang, Sumatra (N.E.I.), refinery in 1940. This plant employed a slurry of $AlCl_3$ in liquid butane as the catalyst, with anhyd. hydrogen chloride (HCl) as catalyst promoter. Although design production of isobutane was reached, mechanical difficulties associated with the handling of the catalyst and promoter were troublesome and low catalyst life was obtained. The experimental operation of this plant led to further investigation in laboratory and pilot plant equipment, and a greatly improved process, which is now in widespread use, was the result. The improved process was developed through the cooperative efforts of the technical staffs of the Anglo-Iranian Oil Company, and the Standard Oil Development Company, and is commonly referred to as the "Anglo-Jersey" process.

In the revised process vapor-phase conditions are employed using $AlCl_3$ adsorbed on bauxite as the catalyst. An important feature of the improved process is a technique for adding aluminum chloride to the reactor by sublimation into the butane feed and adsorption on Porocel (a low iron-content bauxite), thereby making it possible to maintain the aluminum chloride concentration on the Porocel within an optimum range and to extend the use of a single charge of the Porocel almost indefinitely. Besides providing a relatively large surface for the aluminum chloride which results in a highly active catalyst, the retentive characteristics of the adsorbent make it possible to operate at vapor-phase conditions under which aluminum chloride would normally have a substantial vapor pressure, with very slight loss of aluminum chloride from the reactor. Dispersion of the aluminum chloride on the carrier also prevents its degradation to sludge, which would otherwise occur under the operating conditions employed. The volatility characteristics of $AlCl_3$ thus have been converted from a liability into an asset.

FIG. 1. Pentane isomerization with $AlCl_3$ on Porocel catalyst. Effect of benzene content of feed



*Presented at the regional meeting of the American Institute of Chemical Engineers, Galveston, Texas, March, 1946. Published in *AIChE Transactions*, Vol. 42, No. 4, August 25, 1946.

TABLE 1.
Process Data—Pentane Isomerization

Feed—n-pentane (dry, well-fractionated, olefin-free) + 0.2 vol. per cent benzene.
Catalyst—$AlCl_3$ on Porocel.
Reactor conditions:
Temperature—200F.
Pressure—250 psig.
Feed rate—1.0 v/v/hr.*
HCl concentration—1.0 wt per cent (2.0 mole per cent) based on feed.
H_2 concentration—1.0 mole per cent based on feed.
Results
Isopentane yield—60 per cent.
Selectivity—99+per cent.
Catalyst life—120 gal i—C_5/lb $AlCl_3$.
—18+ gal i—C_5/lb Porocel.
*Volumes liquid hydrocarbon feed/vol. Porocel/hr.

The process development work was carried out in laboratory and pilot plant equipment ranging in capacity up to about 2 gal an hr feed rate. The largest pilot unit was designed to simulate the proposed commercial operation as closely as possible and included means of recovering and recirculating hydrogen chloride (the catalyst promoter) as in commercial operation. A more detailed description of the process is given with the discussion of its commercial application in a later section of this paper.

Pentane isomerization. Following the development of the Anglo-Jersey butane isomerization process, attempts were made to apply the same catalyst and operating technique to the isomerization of normal pentane. Poor results were obtained at first; side reactions (chiefly the formation of isobutane and 2-methyl pentane) predominated and the $AlCl_3$ was degraded quickly to a sludge or lost its activity. A highly selective, sludge-free isomerization process was developed, however, by using aluminum chloride on Porocel under milder, liquid-phase conditions and by the addition of a small, carefully controlled amount of benzene to the feed. The effectiveness of benzene as an inhibitor of side reactions, and the critical nature of the benzene concentration are illustrated in Fig. 1. It will be observed that the addition of 0.2 vol per cent benzene to the feed raises the selectivity,† from about 30 per cent to 99-100 per cent. The optimum benzene concentration is close to 0.2 per cent, larger amounts causing reduced conversion and catalyst life although selectivity remains high. Incidentally, it was found that no appreciable consumption of the benzene occurs.

Typical operating conditions and results of the Jersey pentane isomerization process are summarized in Table 1.

The reactor is charged with Porocel, and $AlCl_3$ is added, by solution in the feed and adsorption on the Porocel, as required to establish and maintain catalyst activity. The operating conditions are such that the reactor contents are entirely in liquid phase. Feed rates lower than 1.0 *v/v/*hr may be employed if desired, with some saving in catalyst consumption. An HCl concentration of 1.0 weight per cent is about optimum, with lower HCl contents reducing catalyst activity and life and higher concentrations tending to impair the selectivity of the operation. A hydrogen concentration of 1.0 mole per cent was chosen largely because this amount can be dissolved in the feed stock at a reasonable pressure and recycled conveniently along with the HCl. Considerably lower catalyst activity and life are obtained if the hydrogen is omitted.

Conversion may be controlled by adjusting feed rate and temperature, within suitable limits, and by the $AlCl_3$ input. It is preferred to maintain the active $AlCl_3$ content of the catalyst relatively constant so as to minimize the necessity for changing the operating conditions. This may be done either by making small, frequent additions of $AlCl_3$ or by continuous addition of $AlCl_3$ to the reactor at a controlled rate.

Although the solubility of $AlCl_3$ in liquid pentane at the reactor conditions (200 F) is approximately 0.8 weight per cent, the loss of $AlCl_3$ from the reactor by solution is very much lower, normally of the order of 0.01 weight per cent due to the adsorptivity of the Porocel.

A simplified flow plan for the process is presented as Fig. 2. The n-pentane feed is pumped through a heater to the reactor, with a controlled amount going through an $AlCl_3$ pickup drum. The reactor effluent (normally about 60 per cent isopentane) flows to a disengaging drum, where any undissolved gas is released, and is then pumped to the stripper, in which a stream rich in HCl and hydrogen is taken overhead. The bottoms product is released to a cooler, caustic wash, and fractionation facilities. In the flow plan shown the recycle HCl and hydrogen are introduced at the reactor inlet and the lower part of the reactor is utilized as an absorber. Alternatively, a separate absorber vessel may be employed.

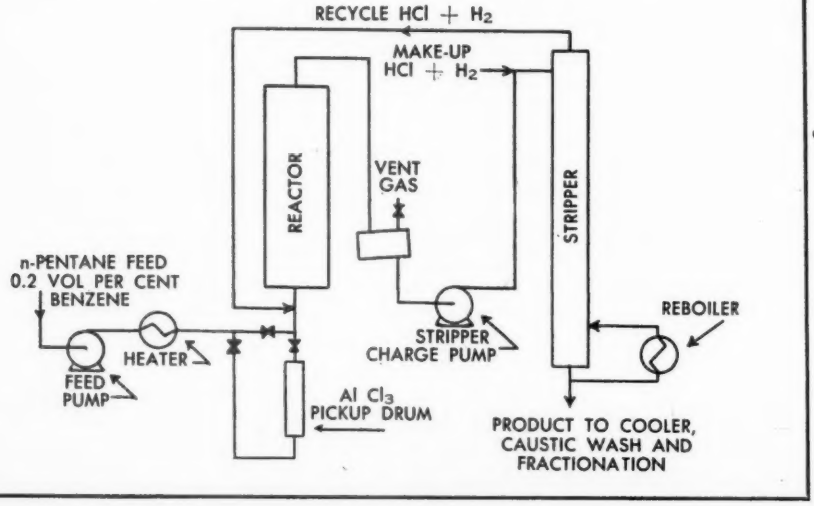
● **Commercial application—butane isomerization.** The development of the alkylation process, which utilizes isobutane together with olefins to produce high octane gasoline, and the wartime demand for enormous quantities of aviation gasoline resulted in a rapid large-scale application of the Anglo-Jersey butane isomerization process. The first commercial plant to use the process was built by the Humble Oil and Refining Company, at Baytown, Texas, and started operation in October, 1942. Designed to produce 1200 bbl per day of isobutane, the output of this plant was subsequently more than doubled. Complete information on plant design and operating technique was distributed to other petroleum refiners through the Aviation Gasoline Advisory Committee of the Petroleum Administration for War, with the result that a total of twelve plants (eight not affiliated with the developers of the process), having a combined capacity of about 25,000 bbl per day of isobutane, were using the process during the latter part of the war.

TABLE 2.
Process Data—Butane Isomerization

Temperature—250-300F.
Pressure—200-250 psi.
Feed rate—0.5-1.0 v/v/hr.*
HCl concentration—6 wt per cent based on feed.
Conversion—40-50 per cent.
Selectivity†—95 per cent.
Catalyst life—180 gal i—C_4/lb $AlCl_3$
— 60 gal i—C_4/lb Porocel
*Volumes liquid hydrocarbon feed/vol. Porocel/hr.
†$\frac{\text{Isobutane produced}}{\text{n-butane consumed}} = 100$

Description of a typical plant. A simplified flow plan of a typical butane-isomerization plant, designed by the Standard Oil Development Company and constructed and operated by Lago Oil and Transport Company, Ltd., at Aruba, N.W.I., is given in Fig. 3. Normal butane feed from storage flows through a drier containing calcium chloride. The dried butane is vaporized and superheated to the desired temperature and flows to the reactor, which is charged with substan-

FIG. 2. Simplified flow plan. Jersey pentane isomerization process.



†per cent selectivity = $\frac{\text{isopentane produced}}{\text{n-pentane consumed}} \times 100$

tially dehydrated, low iron-content bauxite (Porocel). A controlled portion of the superheated vapors may pass through a vessel charged with aluminum chloride prior to entering the reactor. Aluminum chloride thus is vaporized and fed into the reactor as required and is adsorbed on the Porocel. This technique maintains the catalyst in a relatively uniform and high state of activity and allows continuous operation for periods of time extending up to several months. Anhyd. hydrogen chloride, which is employed as a catalyst promoter, is combined with the incoming feed near the reactor inlet. Typical reactor conditions and results are shown in Table 2.

The vapors leaving the reactor are condensed and cooled and flow to an accumulator drum. Any uncondensed gas may be released at this point. The liquid is pumped to the hydrogen chloride stripper, a conventional 20-plate fractionating tower in which a vapor stream rich in HCl is taken overhead for recirculation. The bottoms from this tower flow to the caustic wash system for removal of any residual HCl and of traces of aluminum chloride which may be carried from the reactor, and thence to the fractionating system. The fractionating equipment handles the effluent from both the isomerization plant and an adjoining alkylation plant, separating isobutane to charge to the alkylation plant, normal butane feed for the isomerization plant, and alkylate product.

The entire plant is constructed of carbon steel, and most major vessels and other essential items employed were existing equipment salvaged or converted from other uses. The utilization of existing equipment made possible a large saving in time, and materials that were scarce, at a time when the need for isobutane was critical.

It was necessary to install facilities for manufacturing anhyd. HCl to supply the isomerization unit, and the salt-sulphuric acid method was selected. (Alternate methods in use in other isomerization plants include the dehydration of muriatic acid with sulphuric acid, and the combustion of hydrogen with chlorine, the choice of process depending chiefly on the location of the plant with respect to raw materials.) The HCl generating system was designed to be large enough to replace the entire isomerization plant inventory of HCl within three to five days if necessary due to losses or in starting up, although normal losses are comparatively low. Dried salt (NaCl) is charged batchwise to the HCl generator and 98 per cent sulphuric acid added at the rate desired for HCl production. The generator is steam-jacketed and is maintained at a temperature of 175-250 F. A stream of butane vapor is introduced at the bottom of the generator to effect the removal of HCl as formed and to provide agitation. The residue in the generator is removed as a slurry after an excess of H_2SO_4 has been added.

HCl leaving the generator is contacted countercurrently with 98 per cent sulphuric acid to reduce its moisture content to a very low value and the dried HCl is then absorbed in a dried and chilled light alkylate stream and pumped into the isomerization plant. A low-pressure absorption system was chosen in preference to the use of a compressor due to difficulties anticipated in the operation of a compressor on a concentrated HCl gas stream, and in preference to generating HCl at the isomerization plant pressure (200-250 psi) in order to allow the use of existing steel equipment for HCl generation without undue hazard.

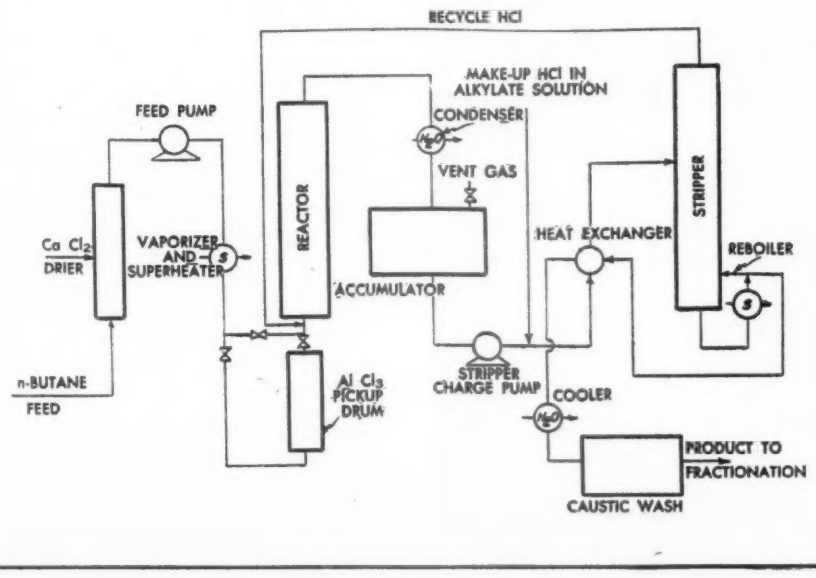
Operating experience. Although a number of operating difficulties were encountered in the initial operation of the various plants, service factors above 90 per cent were generally attained. It had been found in the development of the process that high-purity feed stock was essential for best operation, and the purity of the feed has proved to be a limiting factor in the output of some plants. The olefin content of the feed is especially critical, concentrations higher than about 0.01 per cent causing the degradation of $AlCl_3$ to sludge, thus deactivating the catalyst and tending to plug the catalyst bed. The sludge also is quite corrosive to steel. Since the isomerization feed in most plants includes normal butane from the alkylation process (to which C_4 olefins are fed) the possibility of contaminating the feed with olefins is always present, but fortunately good alkylation plant conditions result in essentially complete clean-up of olefins, and the strict requirement for isomerization plant feed can be met. The presence of pentanes in the isomerization plant feed is also harmful to the catalyst and the capacity of the plant fractionating equipment to produce an essentially pentane-free feed (less than 0.5 per cent) is one of the limiting factors encountered in pushing production above design. Any moisture in the feed reacts with aluminum chloride and reduces the life of the catalyst, thus placing a premium on effective feed-drying.

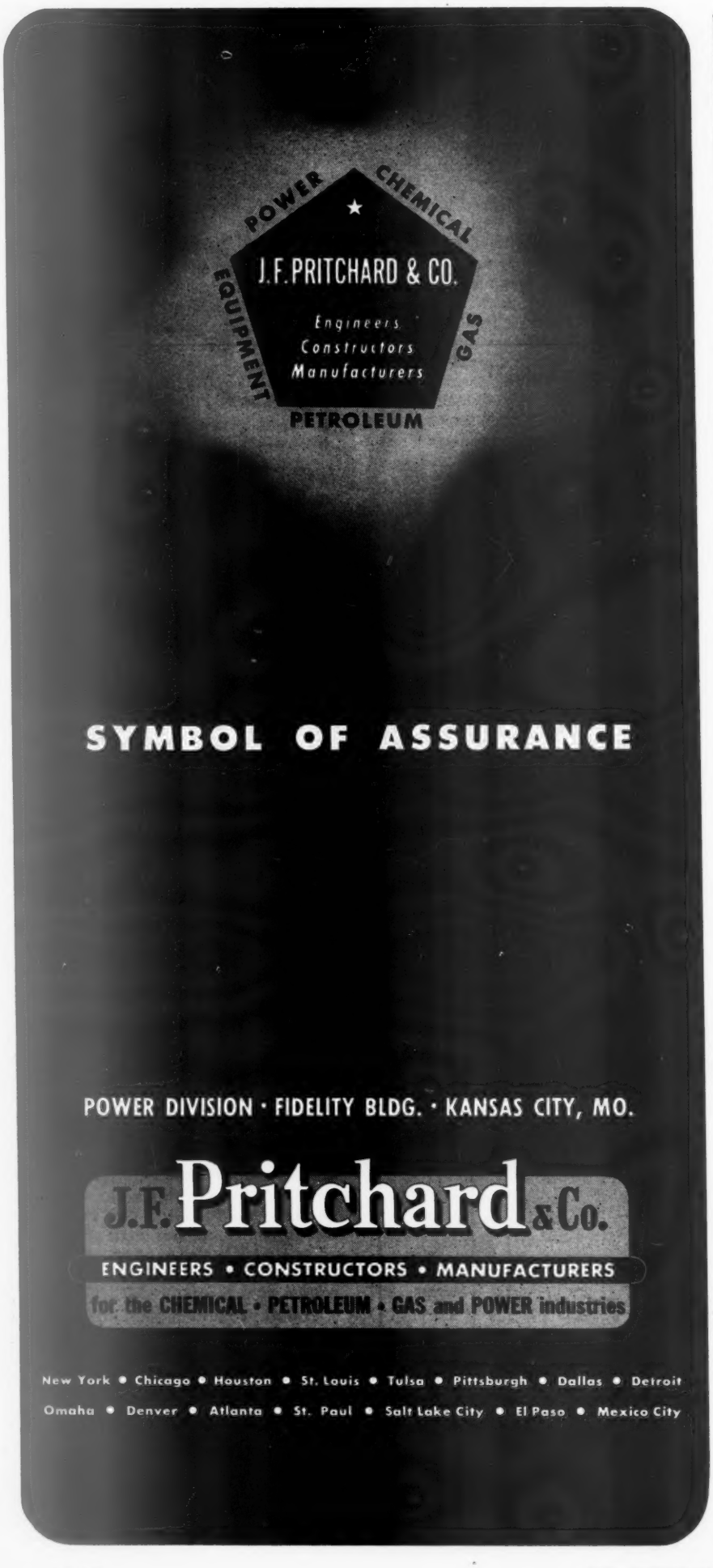
The life of the catalyst has varied considerably depending on feed stock purity and the conditions of operation. The production of 150-200 gal isobutane per lb $AlCl_3$ charged may be considered typical, but as much as 1000 gal isobutane per lb has been obtained under very favorable conditions. The life of a charge of Porocel has been found to be about three months when operating at severe conditions and high throughput, while in a plant which is limited by factors other than the reactor size and operated at milder reactor conditions a single charge of Porocel has lasted as long as a year. During the war all plants were operated for maximum production, with catalyst life a secondary consideration.

A very small but appreciable quantity of $AlCl_3$ is carried from the reactor in the product stream during normal operations. The rate of carry-over increases as the catalyst base becomes saturated with $AlCl_3$ and its degradation products, and is greater at high output conditions (high temperature and feed rate). The normal rate of carry-over can be tolerated, but excessive carry-over results in the deposition of aluminum chloride in the product condenser, HCl stripper reboiler and stripper product cooler. Difficulty of this nature was reduced by improved control of the $AlCl_3$ input and operating conditions, improvement in feed quality (to retard deterioration of the catalyst bed) and minor changes in equipment design.

It will be noted in the flow plan (Fig. 3) that several heat exchangers are located where anhyd. HCl is present on one side of the heat-exchange tubes and water or steam on the other side. As long as no leakage occurs, ordinary steel tubes do not corrode appreciably, and steel is generally used. Any slight leak-

FIG. 3. Flow plan. Butane isomerization plant.

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It is estimated that at the peak of World War II demand the U. S. oil industry supplied 1,600,000 barrels of oil a day for direct military requirements alone.

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age, however, results in the formation of aqueous HCl, which causes rapid corrosion and enlarges the leak. The pressure is normally kept lower on the aqueous side of the heat exchangers so that any leakage will be outward, and the steam or water effluent is checked frequently for acidity in order to detect leaks promptly. Generally it has been found advisable to install stand-by heat-exchange equipment in order to insure long periods of uninterrupted operation at high production levels.

The presence of any moisture in the product recovery and recycle systems (where HCl is present) causes corrosion and the formation of iron chloride ($FeCl_2$) which fouls the equipment. The moisture tends to concentrate in the upper part of the HCl stripper in particular. The major sources of moisture were found to be the residual water content of the Porocel charged, and water formed by the reaction of HCl with iron oxide contained in the Porocel or present as rust inside the equipment. By treating each charge of Porocel with anhyd. HCl vapor and purging thoroughly at or above the operating temperature prior to use, trouble of this type was practically eliminated.

● **Outlook.** At the close of the war, operation of most butane isomerization plants was discontinued. Future operation of these plants is dependent upon the local supply of isobutane from other sources (isobutane occurs naturally and as a by-product of both catalytic and thermal cracking) and the quantity required for alkylation, which in turn depends on the volume and octane level of aviation gasoline production. Other uses of isobutane as a chemical raw material will undoubtedly increase.

The Jersey pentane isomerization process has not been utilized commercially, but could be employed quite readily in existing butane isomerization plants. Its use to increase the general octane level of motor gasoline supplies is currently under consideration. The isomerization process is an efficient tool to aid the refiner in making optimum utilization of light petroleum fractions, and its application is expected to increase.

The author wishes to point out that credit for the successful process developments described is shared by a great many individuals both in the organizations mentioned and in the various plants using the process. The helpful advice of N. F. Myers, F. W. Schumacher, and W. H. Rupp, all of the Standard Oil Development Company, in the preparation of this paper is also acknowledged.

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Calculation of number of theoretical plates for rectifying column*

By A. E. STOPPEL, University of Minnesota

By extending the equilibrium curve and operating line of the typical McCabe-Thiele distillation diagram beyond their usual limits, the operating line will be found to cut the equilibrium curve at two points, once on the chart proper, and again somewhere outside the chart. The number of theoretical plates required to operate the column may be expressed as a simple power function of these two points of intersection.

THE problem of the rapid calculation of the number of theoretical plates required to effect a given separation by distillation of a two-component system was studied by a number of investigators[1-4,7,8] who have each approached the problem in a variety of ways. Some of the proposed methods make simplifying assumptions and must be regarded as approximate when used over wide ranges of operating variables. Others are empirical in nature and involve the use of charts. A few are exact for infinite reflux but do not hold at lower reflux ratios. A method which is exact for any reflux ratio, purity of overhead product or waste, or condition of feed, but which assumes constancy of the relative volatility, was proposed by Smoker[7]. More recently Harbert[5] developed equations to "jump over" a number of plates in a single step.

The method described here leads to an expression algebraically identical to the equation proposed by Smoker[7]. By proper choice of constants picked from a modified McCabe-Thiele chart, the equation may be expressed rather simply and in a form resembling the expression obtained by Fenske[3] for conditions at total reflux.

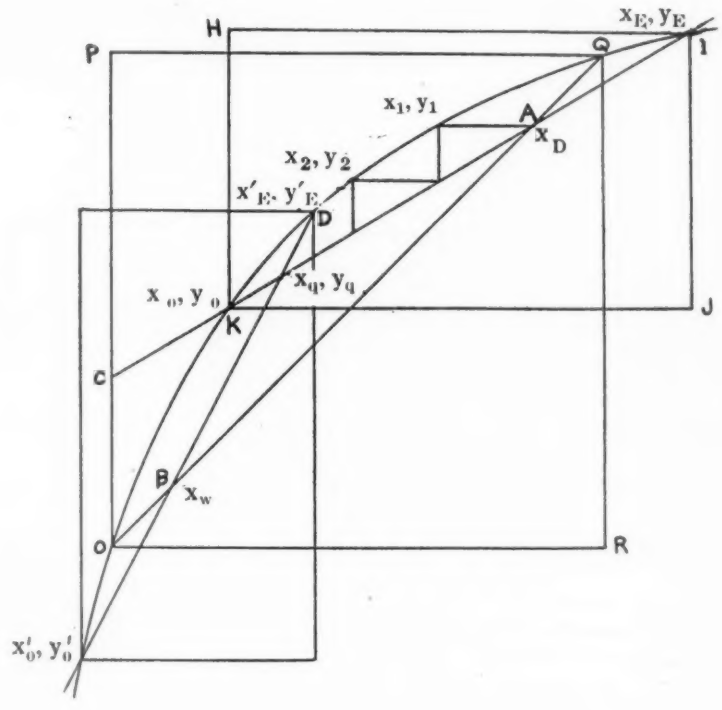
Fig. 1 represents an expansion of the familiar McCabe-Thiele[6] diagram. Within square OPQR are represented equilibrium curve ODQ and two operating lines AK and BD. Extension of the equilibrium curve and rectifying line to the right to the point of intersection at I permits the construction of rectangle HIJK, within which are represented the operating conditions of the section of the column above the feed plate. The rectifying line is the diagonal of this rectangle; this suggests that the upper part of the column is apparently operating at total reflux.

Points (x_0, y_0) and (x_E, y_E), the intersections of the operating line and the equilibrium curve, may be located by solving simultaneously the equation of the operating line, $y = mx + c$, and the equilibrium relation, $y(1-x)/x(1-y) = a$, obtaining: $m(a-1)x^2 + (m - a + ac - c)x + c = 0$ and $(a-1)y^2 + (m - a - ac + c)y + ac = 0$. The solution of these quadratics for x_0, x_E, y_0, and y_E is obviously somewhat involved and leads to cumbersome expressions. However, the products x_0x_E and y_0y_E are useful and are simply stated: $y_0y_E = ac/(a-1)$ and $x_0x_E = c/m(a-1)$. Dividing these equations and rearranging gives $y_0y_E/ax_0x_E = m$, and, since $m = (y_E - y_0)/(x_E - x_0)$,

$$(y_E - y_0)/(x_E - x_0) = y_0y_E/ax_0x_E \quad . . . . . (1)$$

*First published in *Industrial and Engineering Chemistry*, December, 1946.

FIG. 1. Modified McCabe-Thiele diagram for distillation column.



Consider the arc cut by a straight line through points (x_0, y_0) and (x_1, y_1). From analogy to Equation 1 this leads to

$$(y_1 - y_0)/(x_1 - x_0) = y_1y_0/ax_1x_0 \quad . . . . . (2)$$

and, for the straight line through points (x_1, y_1) and (x_E, y_E),

$$(y_E - y_1)/(x_E - x_1) = y_1y_E/ax_1x_E \quad . . . . . (3)$$

Dividing Equation 2 by Equation 3 gives

$$\frac{(y_1-y_0)\ (x_E-x_1)}{(x_1-x_0)\ (y_E-y_1)} = \frac{y_0x_E}{x_0y_E} \quad . . (4)$$

which represents ratios of slopes from the top plate to opposite corners of the rectangle.

A ratio around point (x_2, y_2) results in the expression

$$\frac{(y_2-y_0)\ (x_E-x_2)}{(x_2-x_0)\ (y_E-y_2)} = \frac{y_0x_E}{x_0y_E} \quad . . (5)$$

A similar expression may be written for each plate above the feed plate. The product of all these expressions leads to the series

$$\frac{(y_1-y_0)\ (x_E-x_1)\ (y_2-y_0)(x_E-x_2)\ (y_3-y_0)\ \ldots\ (y'_q-y_0)\ (x_E-x_q)}{(x_1-x_0)\ (y_E-y_1)\ (x_2-x_0)(y_E-y_2)\ (x_3-x_0)\ \ldots\ (x_q-x_0)\ (y_E-y'_q)} = \left(\frac{y_0x_E}{x_0y_E}\right)^{n_1} \quad . . . . . (6)$$

In Fig. 1 point (x_i, y_i) falls on the diagonal of the rectangle. It is obvious from the geometrical construction that area $(x_E - x_1)\ (y_2 - y_0) =$ area $(y_E - y_2)\ (x_1 - x_0)$. Also $(x_E - x_2)\ (y_3 - y_0) = (x_2 - x_0)\ (y_E - y_3)$, etc. Cancellation of these equalities from Equation 6 gives

$$\frac{(y_1-y_0)\ (x_E-x_q)}{(y_E-y_1)\ (x_q-x_0)} = \left(\frac{y_0x_E}{x_0y_E}\right)^{n_1} \quad (7)$$

Fig. 1430
Iron Body Gate

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which is a general equation for calculating the number of plates above the feed plate.

For conditions below the feed plate the equilibrium curve is extended below the origin to permit intersection with the stripping line at points (x'_E, y'_E) and (x'_0, y'_0). A rectangle is constructed with these points on the diagonal. The derivation of the equation for the number of plates below the feed plate is entirely analogous to that given and result in the equation

$$\frac{(y_q - y'_0)}{(y'_E - y_q)}\frac{(x'_E - x_w)}{(x_w - x'_0)} = \left(\frac{y'_0 x'_E}{x'_0 y'_E}\right)^{n_2} \quad (8)$$

The total number of plates required for the entire column is the sum of n_1 and n_2, where n_2 includes the still pot as one of the plates in the stripping section.

Equations 7 and 8 are algebraically identical to those proposed by Smoker[7], although the similarity is by no means obvious. When this derivation is applied to conditions at total reflux, the equation reduces to

$$y_1(1 - x_w)/x_w(1 - y_1) = a^n,$$

as given by Fenske[3].

Nomenclature

x = mole fraction of more volatile component in liquid,
y = mole fraction of more volatile component in vapor,
y_1 = mole fraction of more volatile component in overhead product,
x_w = mole fraction of more volatile component in waste,
a = relative volatility,
m = slope of rectifying line,
c = y-intercept of rectifying line on x, y diagram when $x = 0$,
x_0, y_0 = lower point of intersection of rectifying line and equilibrium curve,
x_E, y_E = upper point of intersection of rectifying line and equilibrium curve,
x'_0, y'_0 and x'_E, y'_E = lower and upper points of intersection of stripping line and equilibrium curve, respectively,
x_q, y_q = point of intersection of rectifying and stripping lines,
y_q' = equilibrium value of y when $x = x_q$,
n_1 = number of theoretical plates for rectifying section,
n_2 = number of theoretical plates for stripping section.

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Predicting commercial heat transfer coefficients*

By E. P. BREIDENBACH and H. E. O'CONNELL, Ethyl Corporation

● **Abstract.** Approximately 80 over-all heat transfer coefficients were obtained on 24 commercial heat exchangers. These are reported and compared (where possible) with the theoretical coefficients that could be predicted from correlations available in the literature. Good agreement was obtained between the actual and theoretical coefficients for:

1. Partial condensation of hydrocarbons and chlorinated hydrocarbons with water and with propane refrigerant.
2. Total condensation of chlorinated hydrocarbons with water.
3. Liquid-liquid exchangers where heat was interchanged between chlorinated hydrocarbons and water and between water and water.
4. Gas exchangers.

Theoretical coefficients could not be predicted for reboilers, mainly because neither the boiling film nor the fouling film could be determined; however, heat flux densities of from 8000 to 10,000 Btu/(hr) (sq ft) at a temperature difference of 80 F should give conservative values in the design of reboilers for boiling chlorinated hydrocarbons, low boiling hydrocarbons, and hydrochloric acid solutions with condensing steam.

● **Introduction.** The literature is replete with methods of calculating theoretical heat transfer coefficients for single films, but very little attention has been given to the most important problem of predicting commercial overall coefficients. Nelson[8] recognized this deficiency and attempted to show the application of theoretical methods to practice by comparing calculated overall heat transfer coefficiencies with actual coefficients obtained in refinery practice. Unfortunately, in the cases studied, the fouling present overshadowed the effect of the individual films and the results were not conclusive. Nelson[8] felt that the inability to compute heat transfer rates with accuracy was not due so much to inadequacies in the transfer rate data, as to an inability to predict accurate fouling tendencies.

In the past several years, many heat transfer data have been collected for systems where the fouling factors, in most cases, were small or could be accurately predicted. Consequently, these coefficients were compared with coefficients calculated by known means.

This paper does not advance any new theories in heat transfer but attempts to show that present theories can be used to predict commercial coefficients with reasonable accuracy. It was felt that such information would be of special value to the students of chemical engineering as well as the practicing engineer.

● **Commercial overall heat transfer coefficients.** Approximately 80 heat transfer coefficients were obtained on 24 commercial exchangers. The results of these tests are summarized in Tables 2-6.

The overall heat transfer coefficients were calculated from the equation

$$U = q/(A)(\Delta t) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Where:

U = overall heat transfer coefficient, Btu/(hr) (sq ft) (°F),
q = heat transferred, Btu/hr,
A = area of the heating surface, sq ft,
Δt = temperature difference, ° F.

The heat transferred, q, was taken as the more reliable of either the heat input or out put (if they were of equal reliability, the average was taken). For water flows, the heat transferred was calculated from flow, obtained by an orifice type meter, and the temperature of the water entering and leaving (from calibrated thermometers or thermocouples). For refrigerant flows, the heat was obtained from the flow, metered as a liquid in an orifice-type flow meter and the enthalpy change from temperature and pressure conditions of the liquid entering and vapor leaving the exchanger. For steam, the heat was determined from the flow and the thermal conditions of the steam entering and the condensate leaving. The flow was determined by weighing the condensate in a tared drum with the proper correction being made for the portion flashed upon reduction to atmospheric pressure. Most of the process stream flows were determined from heat and material balances around the exchangers and consequently offer no check on the refrigerant or steam heat flows.

The temperature difference was in most cases the log mean temperature difference with the proper correction being made for non-true counter-current flow, McAdams[6]. In some cases, for example, boiling a pure liquid with steam, the use of the arithmetic mean temperature difference was satisfactory.

The actual heat transfer coefficients reported in Tables 2-6 are of value in themselves for they permit a quick estimation of coefficients for similar systems and have been of great value to the authors in preliminary process design work. Moreover, these coefficients were compared with theoretical overall coefficients to show the validity of the available theoretical methods.

● **Calculation of theoretical overall heat transfer coefficients.** Theoretical overall heat transfer coefficients may be calculated by the following *approximate* equation:

$$U = \frac{1}{\frac{1}{h_1} + \frac{1}{h_{f1}} + \frac{L}{k}\cdot\frac{D_1}{D_{av}} + \frac{D_1}{h_{f2}D} + \frac{D_1}{h_2 D_2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Where:

h_1 = heat transfer coefficient on tube side, Btu/(hr) (sq ft) (°F),
h_{f1} = heat transfer coefficient of the fouling material on the tube side,
L = thickness of tube, ft,
k = thermal conductivity of metal. Btu/(hr) (sq ft) (°F/ft),
h_{f2} = heat transfer coefficient of the fouling material on the shell side,
h_2 = heat transfer coefficient on the shell side,
D_1 = inside diameter of tube (ft),
D_2 = outside diameter of tube (ft),
D_{av} = average diameter of tube (ft).

Methods for evaluating the individual heat transfer coefficients available in the literature and applicable to this study are summarized below. For a more comprehensive review, the reader is referred to McAdams[6].

Fouling. Fouling in heat exchangers may be defined as the resistance to heat transfer resulting from the deposition of materials on the heat transfer surface. Fouling may result from the formation of a scale such as calcium carbonate, from carbon formation, from algae formation, or from foreign materials introduced with the stream being processed. Unfortunately, the determination of the extent of fouling to be expected is complicated because the fouling varies from day to day, plant to plant, system to system, and exchanger to exchanger. Values of fouling factors have been given by McAdams[6], Nelson[7], and the Tubular Manufacturers Association[9]. These were supplemented with fouling factors determined in the plant, and the values pertinent to the present study are given

TABLE 1. Fouling factors.

Service	Fouling factors*
Gases	
Steam	0
Hydrogen chloride	3
Low boiling hydrocarbons	1
Chlorinated hydrocarbons	1
Liquids†	
Water (either closed system or treated cooling tower water)	2-3
Low boiling hydrocarbons	1-2
Chlorinated hydrocarbons	1
Hydrochloric acid	0

*The fouling factor, f.f. $= 10^3/h_f$.
†These fouling factors do not hold for boiling liquids.

*Published in *AIChE Transactions*, Vol. 42, Nos. 5-6, October-December 1946.

in Table 1. The fouling factor is related to the heat transfer coefficient by the relationship, $h_f = 10^3$/fouling factor.

Heating and cooling fluids inside tubes. For the conditions found in this study, the Dittus and Boelter[4] equation, below, is considered best for heating or cooling ordinary fluids (liquids and gases) flowing in either vertical or horizontal tubes or pipes, provided that they have viscosities not more than twice that of water and values of DG/μ exceeding 2100.

$$h = 0.023\ k/D\ (DG/\mu)^{0.8}(c_p\mu/k)^{0.4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where the terms are defined in the nomenclature.

Heating and cooling fluids outside tubes. BANKS OF TUBES. For heating or cooling (no change of state) liquids or gases flowing normal to banks of unbaffled tubes with values of $D_oG_{max.}/\mu$ exceeding 2000, the equation of Colburn, given in McAdams[6], is recommended.

$$h = ak/D_o(c_p\mu/k)^{1/3}(D_oG_{max.}/\mu)^{0.6} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

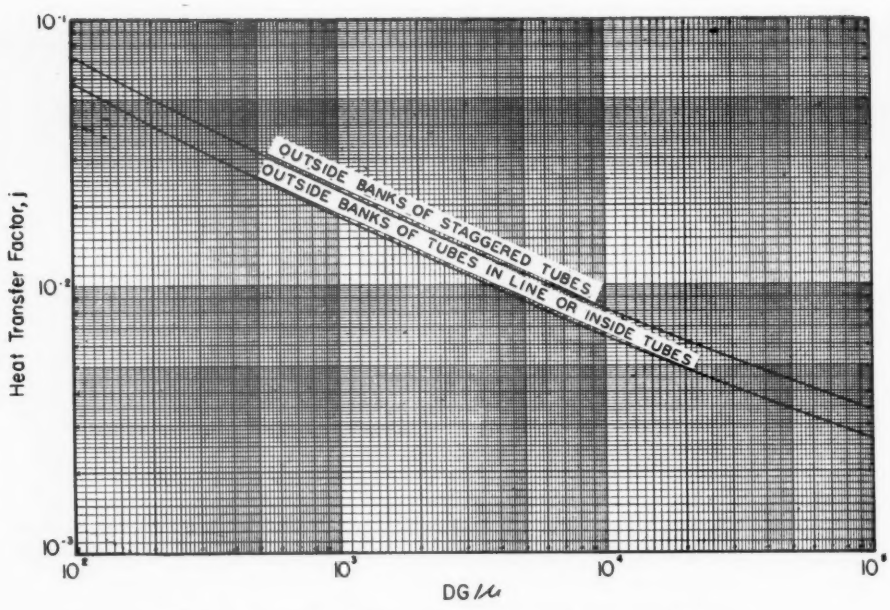


FIG. 1. Heat transfer factor for condensing vapor films.

TABLE 2. Comparisons of actual and calculated heat transfer coefficients for partial condensers.

Test No.	Type	Surface area, sq ft	Fluid flowing in: Tube side	Fluid flowing in: Shell side	Heat load, M Btu/hr	Δt °F	Heat flux density Btu/(hr) (sq ft)	Coefficient, Btu/(hr) (sq ft) (°F): Actual	Coefficient, Btu/(hr) (sq ft) (°F): Calc.	Per cent Deviation*
1	Shell and tube	312	Condensing mixture of chlorinated hydrocarbon and hydrocarbons.	Water	235	30.5	753	24.7	15.5	+ 37.3
2					152	31.4	487	15.5	20.2	— 30.3
3					116.6	27.7	374	13.5	12.6	+ 6.7
4	Shell and tube	59	Condensing mixture of ethanol, hydrogen chloride and water.	Water	526	120.7	8,925	73.8	.....	.....
5	Shell and tube	100	Condensing mixture of chlorinated hydrocarbon and hydrocarbons.	Boiling propane	92.5	40.2	925	23.0	24.4	— 6.1
6					267	84.7	2,670	31.5	36.8	— 16.8
7					284	87.0	2,840	32.6	37.3	— 14.4
8	Shell and tube	1500	Condensing mixture of chlorinated hydrocarbon and hydrocarbons.	Boiling propane	2,460	21.6	1,640	76.0	67.8	+ 10.8
9					2,900	27.3	1,934	70.8	69.8	+ 1.4
10					3,275	33.8	2,180	64.5	66.0	— 2.3
11					2,780	27.1	1,852	68.4	68.5	— 0.2
12					2,910	27.3	1,940	71.0	70.8	+ 0.3
13					3,100	33.9	2,065	61.0	68.8	— 12.8
14					3,320	29.3	2,210	75.5	71.0	+ 6.0
15	Shell and tube	682	Condensing mixture of low boiling hydrocarbons.	Boiling propane	282.9	7.62	415	54.5	43.9	+ 19.5
16	Shell and tube	2000	Condensing mixture of chlorinated hydrocarbon and hydrocarbons.	Boiling ethylene	682	10.2	341	33.4	74.8	—124.0
17					563	6.8	281	41.2	32.4	+ 21.4
18					354	12.9	177	13.7	19.2	— 40.1

*$\frac{\text{actual-calculated}}{\text{actual}}$

TABLE 3. Comparisons of actual and calculated heat transfer coefficients for total condensers.

Test No.	Type	Surface area, sq ft	Fluid flowing in: Tube side	Fluid flowing in: Shell side	Heat load, M Btu/hr	Δt °F	Heat flux density Btu/(hr) (sq ft)	Coefficient, Btu/(hr) (sq ft) (°F): Actual	Coefficient, Btu/(hr) (sq ft) (°F): Calc.	Per cent Deviation*
19	Shell and tube	2400	Water	Condensing chlorinated hydrocarbons.	2,660	14.8	1,109	75.0	54.7	+ 27.1
20					2,135	15.3	890	58.0	53.5	+ 7.8
21					2,560	17.8	1,068	60.1	56.5	+ 6.0
22					3,280	32.5	1,375	42.0	40.3	+ 4.0
23					2,565	37.1	1,070	28.8	39.8	— 38.2
24					2,770	24.8	1,154	46.5	46.0	+ 1.1
25					3,345	28.6	1,395	48.8	.....	.....
26					2,340	17.4	975	56.0	50.6	+ 9.6
27	Shell and tube	354	Water	Condensing chlorinated hydrocarbons.	950	44.7	2,680	60	62.2	— 3.7
28					890	39.9	2,510	63	63.2	— 0.3
29					1,096	44.0	3,095	70.3	68.2	+ 3.0
30	Shell and tube	900	Water	Condensing chlorinated hydrocarbons.	675.0	25.0	750	30.0	60.5	—101.5
31	G-fin	79.8	Water	Condensing chlorinated hydrocarbons.	1,017	93.3	12,760	136.4	120.1	+ 11.9
32					914	84.8	11,460	135.0	113.4	+ 16.0
33	G-fin	212	Water	Condensing chlorinated hydrocarbons.	592.9	40.7	2,800	68.6	93.3	— 36.0
34					844.1	47.2	3,980	84.5	103.0	— 21.9
35					829.3	35.0	3,905	111.7	103.4	+ 7.4

*$\frac{\text{actual-calculated}}{\text{actual}}$

where the constant, a, is equal to 0.33 for staggered and 0.26 for non-staggered tube banks; $G_{max.}$ is based on the minimum free area available for fluid flow. If baffles are used, the coefficient is taken as 0.6 times the value determined from the equation to allow for the leakage that normally occurs around the baffles.

FINNED SECTIONS AND ANNULAR SPACES. The use of the equivalent diameter, D_e, in the Dittus and Boelter[4] equation is recommended. The equivalent diameter may be determined for finned sections by the relationship:

$$D_e = 4S/b$$

where S = cross section open to flow and b = wetted perimeter. The equivalent diameter for annular spaces with the heat flowing through the inner pipe is determined by the following equation:

$$D_e = (D_2^2 - D_1^2)/D_1$$

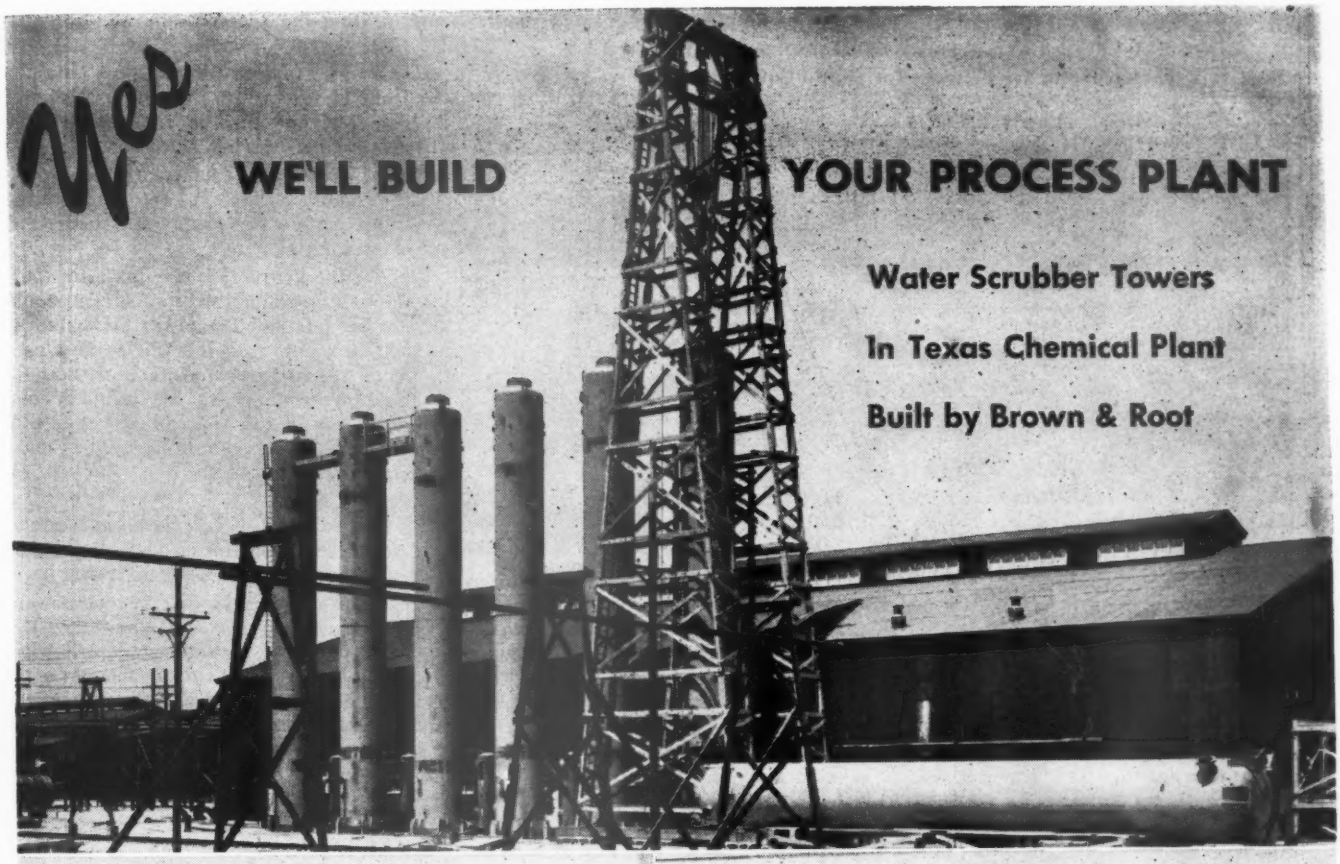
Condensing vapor films. The coefficient for film-type condensation of vapors outside banks of tubes (or single finned tubes) may be approximated from the Colburn[3] equation:

$$h = jc_pG_c(c_p\mu/k)^{-2/3} \quad . \quad . \quad . \quad . \quad (5)$$

where j is defined as the heat transfer factor, values of which may be taken from Fig. 1 (for finned sections, use the lower curve), and G_c is the mass velocity of the condensate film, which, according to Atkins[1], may be expressed by the following equation:

$$G_c = 36{,}000 + EG_v(\rho_l/\rho_v)^{1/2} \quad . \quad (6)$$

where 36,000 is the component attributable to gravity and E is a constant to correct for the incomplete interaction between the condensate and vapor films, being 0.3 for a horizontal travel of condensate of more than 200 in., 0.4 for travel of from 50 to 200 in., and 0.5 when the bundle is vertical and for finned sections. This equation may be used for both pure vapors and mixtures of condensable and non-condensable vapors.



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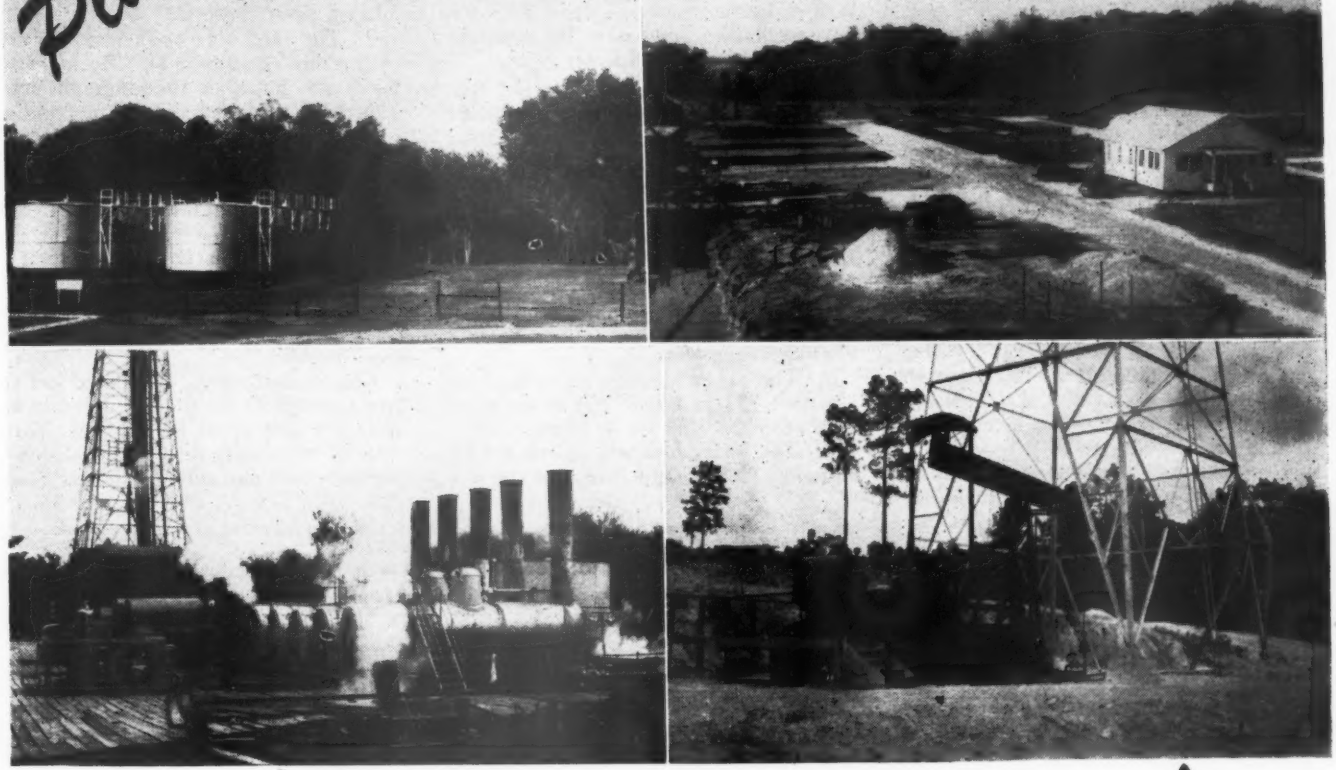

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TABLE 4. Comparisons of actual and calculated heat transfer coefficients for liquid-liquid exchangers.

Test No.	Type	Surface area, sq ft	Fluid flowing in		Heat load, M Btu/hr	Δt °F	Heat flux density Btu/(hr) (sq ft)	Coefficient, Btu/(hr) (sq ft) (°F)		Per cent Deviation*
			Tube side	Shell side				Actual	Calc.	
36	Shell and tube	2465	Impure chlorinated hydrocarbons.	Water	785	2.83	318	112	107.6	+ 4.0
37					490	1.48	199	134	112.6	+ 15.9
38					2,330	11.15	945	84.7	83.9	+ 0.9
39					1,280	6.46	520	80.1	80.4	− 0.4
40	Shell and tube	980	Water	Water	6,820	51.1	6,960	136.1	133.6	+ 1.8
41	G-fin	212	Water	Chlorinated hydrocarbon.	182	23.8	858	36.0	36.1	− 0.3
42					155	18.9	730	38.6	32.6	+ 15.6
43	Vertical	1575	Impure chlorinated hydrocarbon.	Water	649	35.0	411	11.8	.....	.....
44	Shell and tube				955	41.0	606	14.8	.....	.....
45					1,150	27.4	730	26.7	.....	.....

*actual-calculated / actual

In the case of total condensation, the vapor film resistance is zero, but the effect of vapor drag, G_v, must be taken into account for determining G_c. For this case, use G_v equal to one-half the total condensate (average of 100 and 0 per cent vapor).

Vapor film in the presence of condensing vapor films. The resistance of the vapor film in contact with a condensing vapor film may be determined by the equation of Atkins[1], which was derived from the Colburn[3] equation (5 above).

$$1/h = \frac{(S)\,(T.R.)}{(q)\,(j)}\,(c_p\mu/k)^{2/3} \quad . \quad (7)$$

where S is the cross-section open to flow, sq ft; T.R. is the temperature range, °F, between inlet and outlet; q is the heat transferred; and j is the heat transfer factor, values of which may be taken from Fig. 1.

Boiling liquids. No correlations are available for the prediction of heat transfer to boiling liquids because all the variables which affect the rate of boiling are not known *(see* Drew and Mueller[5]). It is practically impossible therefore to predict the coefficients for reboilers unless experience is had with the system in question. In condensers, however, where a boiling refrigerant is used as a cooling medium, the resistance to heat transfer caused by the boiling film is generally so small in comparison with the condensing film that it contributes but little reduction in the over-all coefficient.

Cross-section open to flow. The cross-section open to flow in the shell side of shell and tube exchangers may be calculated by the following method given by Atkins[1].

1. Determine the net cross-section open to flow by subtracting the area occupied by the tubes from the cross-sectional area of the shell or of the bundle if deflector plates are used.

2. Determine the cut-out segment of the baffle and subtract the area of the tubes passing through it. Call this the free cross-section.

3. Determine the linear dimension of the baffle, W, by the equation [W = inside diameter of shell X (1 — F.C.S./N.C.S.)].

4. Increase the linear dimension by a factor depending on tube layout:

1.5 for ¾-in. OD tubes on 1-in. square pattern.

2.0 for ¾-in. OD tubes on 1-in. triangular pattern.

This gives the lateral dimension, x.

5. Determine the distance between the baffles, y, and calculate the diagonal dimension, z, between the inlet and outlet.

$$z = (x^2 + y^2)^{1/2}$$

6. The cross-section open to flow, S, is determined from the equation

$$S = (N.C.S.)\,(y/z) \quad . \quad . \quad . \quad . \quad (8)$$

● ***Comparison of calculated with actual coefficients.*** The coefficients obtained from tests on commercial apparatus and those calculated by the methods described in the previous section are compared and discussed below. The comparisons are given by exchanger types.

Partial condensers. In a partial condenser, the vapor is cooled with either water or refrigerant, to such an extent that only part of the vapor is condensed. Thus, on the condensing side, there is a vapor film in contact with a condensing film. The overall coefficients for water-cooled condensers were calculated in the following manner.

1. The condensing film was calculated by equation (5) as shown above in *Condensing vapor films.*

2. The vapor film was calculated by equation (7) in *Vapor film in the presence of condensing vapor films.*

3. The water film was calculated by equation (3), the conditions of the test fulfilling the requirements of the equation.

4. The fouling factors were obtained from Table 1 and were two for the water side and one for the condensing chlorinated hydrocarbon side.

5. The above coefficients along with the metal coefficient were substituted into equation (2) to give the theoretical overall coefficient.

For the propane-cooled condensers, the boiling propane film coefficient could not be calculated but was estimated as 500 Btu/(hr) (sq ft) (° F). This estimate was in order inasmuch as the boiling film resistance was negligible in comparison with the controlling vapor film resistance. Care should be used in making such assumptions when the over-all coefficient is more than seventy-five.

Comparisons of calculated and actual over-all heat transfer coefficients for partial condensers are given in Table 2.

Total condensers. In the condensers studied, the vapor was condensed on the shell side with the water coolant flowing through the tubes. The theoretical coefficients were calculated in the same manner as the partial condenser expect that there was no vapor film and consequently no vapor-film resistance. Comparisons of calculated and actual coefficients are given in Table 3.

Liquid to liquid exchangers. The liquid exchangers of the shell and tube type were calculated as follows:

1. The tube side coefficient was calculated by equation (3).

2. The shell side coefficient was calculated by equation (4). The mass velocity was based on the minimum cross section as calculated in *Cross-section open to flow.*

3. The fouling factors were selected from Table 1, and were two for the water side and one for the chlorinated hydrocarbon side.

For the G-Fin exchanger, the shell or fin side coefficient was calculated by equation (3), with the equivalent diameter, D_e, substituted for the internal pipe diameter.

Comparisons of the calculated and actual coefficients for the liquid-liquid exchangers are given in Table 4. Theoretical coefficients for tests 43-45 on a vertical shell and tube exchanger could

TABLE 5. Comparison of actual and calculated heat transfer coefficients for gas exchangers.

Test No.	Type	Surface area, sq ft	Fluid flowing in		Heat load, M Btu/hr	Δt °F	Heat flux density Btu/(hr) (sq ft)	Coefficient, Btu/(hr) (sq ft) (°F)		Per cent Deviation*
			Tube side	Shell side				Actual	Calc.	
46	Horisontal Shell and tube	635	Chlorinated hydrocarbon vapors with small degree of condensation.	Hydrocarbon gases	384	45.6	604	13.3	15.4	− 15.8
47					364	52.4	573	10.9	12.6	− 15.6
48					382	49.2	601	12.2	12.9	− 5.7
49					439	50.6	690	13.6	14.5	− 6.6
50					542	49.8	855	17.1	15.4	+ 10.0
51					532	49.0	839	17.1	15.8	+ 7.6
52					429	47.8	675	14.1	13.9	+ 1.4
53	G-fin	205	Water	Hydrocarbon gas	80	27.4	390	14.2	22.0	− 55.0

*actual-calculated / actual

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SUMMARY OF ECONOMICS FOR VARIOUS REFINERY PROJECTS

Refinery Analysis No.	Crude Capacity BPCD	Gasoline BPCD	Distillate Fuels BPCD	Residual Fuel BPCD	ASTM Octane No.	TEL Ccs/Gal.	Crude Cost ¢/Gal.	By-Product Cost of Gasoline ¢/Gal.	Differential ¢/Gal.	Payout in Years
1	5,000	2,893	1,185	688	83.0	1.9	3.8	4.6	0.8	1.4
2	5,000	2,848	600	1,428	83.5	1.3	3.0	5.0	2.0	2.2
3	5,000	3,281	1,239	286	77.5	1.7	4.2	5.1	0.9	3.5
4	3,000	1,206	870	914	79.0	1.3	4.6	4.9	0.3	2.3
5	6,000	3,673	1,080	1,036	77.5	0.7	3.2	4.2	1.0	3.7
6	4,000	2,842	320	604	79.0	0.7	3.2	4.7	1.5	3.6
7	6,000	3,992	.....	1,566	82.5	0.9	3.0	5.1	2.1	2.9
8	4,000	2,610	400	753	78.0	0.5	3.1	4.6	1.5	2.9
9	12,000	7,787	1,800	1,602	81.0	1.5	2.8	4.0	1.2	1.1
10	5,330	3,812	.....	1,032	80.5	0.5	2.9	4.5	1.6	3.3
11	22,500	15,562	2,250	3,004	80.0	0.6	3.9	5.1	1.2	2.3
12	12,000	5,969	1,025	4,612	82.0	1.1	2.5	3.6	1.1	2.5
13	10,000	5,110	3,963	574	78.0	0.5	3.5	3.9	0.4	1.8
14	3,500	1,764	525	1,069	80.0	1.1	3.1	4.7	1.6	2.2
15	9,000	4,663	2,375	1,662	76.0	0.6	4.6	5.1	0.5	2.2
16	6,750	4,473	1,991	783	81.5	1.5	3.9	4.7	0.8	1.7

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not be calculated because the physical properties of the material flowing on the tube side were unknown.

Gas exchangers. There were only a few examples of gas exchangers in the plant. These included:

1. A shell and tube heat exchanger where heat was recovered from a gas by interchange with a partially condensing vapor. For this case, the gas film was calculated from equation (3) and the condensing vapor and vapor films were calculated as shown under *Partial Condensers.*

2. A G-Fin exchanger where a low boiling hydrocarbon vapor on the fin side was cooled with water. The vapor film was calculated by equation (3) with appropriate correction being made for the extended fin surfaces. The water film was calculated by equation (3).

Comparisons of the calculated and actual coefficients for these cases are given in Table 5.

Reboilers—boiling liquids with condensing steam. Actual coefficients obtained in the plant for boiling liquids with condensing steam are given in Table 6. It was impossible to calculate theoretical coefficients because:

1. The boiling film was controlling. As mentioned previously (*see Boiling liquids*) there are no adequate methods for predicting the boiling film coefficients. This is especially true in horizontal reboilers where the degree of boiling would vary with the height of liquid over the individual tubes.

2. The fouling in the reboilers was much greater than in the other exchangers. The high temperatures encountered in reboilers are most conducive to the decomposition of chlorinated hydrocarbons and the polymerization of unsaturated hydrocarbons.

3. In some cases the steam condensate was sub-cooled. Methods (Colburn, et. al.[2]) are available for estimating the degree of sub-cooling but these are of little value with the uncertainties mentioned.

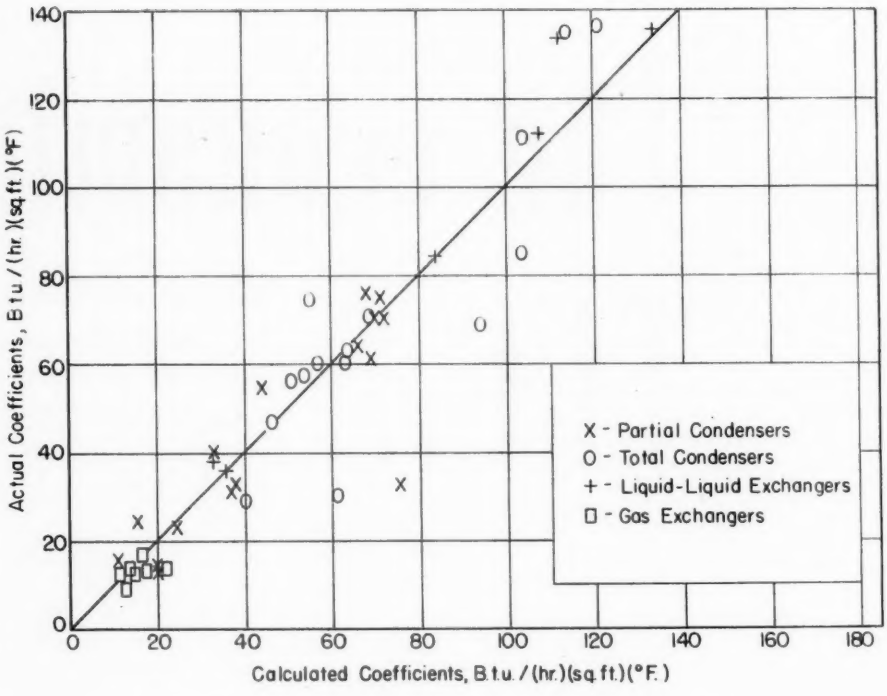

FIG. 2. Comparison of calculated and actual coefficients.

The data on reboiler coefficients, however, do show that:

1. A heat flux density of 8,000 to 10,000 Btu/(hr) (sq ft) at a temperature difference of 80 F is a conservative design value for boiling chlorinated hydrocarbons and hydrocarbons in horizontal reboilers. Actual heat flux densities of more than 13,000 at a temperature difference of approximately 100 F were obtained for a clean reboiler but the heat flux density went down to about 9,000 after a month of service.

2. Coefficients as high as 575 Btu/(hr) (sq ft) (° F) were obtained in a vertical thermosiphon-type reboiler boiling 35 per cent hydrochloric acid; however, for a similar exchanger and service, test No. 74, a coefficient of only 135 was obtained. There was no apparent explanation for the discrepancy.

3. Fouling caused by the decomposition of chlorinated hydrocarbons can seriously lower heat transfer capacity. For example, Tests 54, 55, and 56 were made on the same reboiler over an interval of several month. Test 54, made when the reboiler was commercially clean gave a coefficient of 66.9, which is what could be expected with the low-temperature difference of 12 F; however, with continued use the coefficient decreased until, in Test 56, it was only 20 with a temperature difference of 96 F.

TABLE 6. Heat transfer coefficients for reboilers.

Test No.	Type	Surface area, sq ft	Fluid flowing in		Heat load, M Btu/hr	Δt °F	Heat flux density, Btu/(hr) (sq ft)	Actual coefficient Btu/(hr) (sq ft) (°F)
			Tube side	Shell side				
54	Shell and tube	550	Condensing steam	Boiling chlorinated hydrocarbon	441	12.0	804	66.9
55					580	25.0	1,055	42.2
56					1,063	96.1	1,934	20.1
57					1,263	46.4	2,295	49.6
58					1,221	52.5	2,220	42.3
59					1,121	64.0	2,040	31.8
60	Shell and tube	104	Condensing steam	Boiling chlorinated hydrocarbon	1,325	91.0	12,730	140.0
61					1,406	91.9	13,500	148.6
62					1,295	103.5	12,440	120.2
63					1,046	105.0	10,060	95.9
64					1,041	107.1	10,010	93.5
65					931	96.1	8,950	93.2
66					529	41.8	5,080	121.6
67					802	48.9	7,700	158.0
68					730	42.0	7,020	167.0
69	Shell and tube	550	Boiling mixture of chlorinated hydrocarbon and catalyst	Condensing steam	955	181.0	1,736	9.6
70					984	67.0	1,787	26.7
71					831	101.0	1,511	15.0
72					803	86.0	1,460	17.0
73					1,080	166.0	1,960	11.8
74	Vertical shell and tube (Karbate)	145.4	20 per cent HCl	Condensing steam	1,086	85.1	7,460	135.7
75	Vertical shell and tube (Karbate)	319	35 per cent HCl	Condensing steam	1,763	11.7	5,520	472.0
76					2,913	16.4	9,130	557.0
77					3,182	18.5	9,975	540.0
78					3,814	20.8	11,950	575.0
79	Shell and tube	217	Hot water	Boiling hydrocarbons	529	57.3	2,435	42.5
80	Shell and tube	217	Hot water	Boiling hydrocarbons	804	42.0	3,700	88.4

● **Discussion of results.** The actual and calculated heat transfer coefficients given in Tables 2-5 are compared in Fig. 2 by plotting the calculated coefficients against the actual coefficients. These data were analyzed also by the method of least squares which showed that 95 per cent of the time the maximum absolute deviation is about 11 Btu/(hr) (sq ft) (° F). The percentage deviation will vary depending on the size of the heat transfer coefficient, being as high as 100 per cent for a heat transfer coefficient of 11 Btu/(hr) (sq ft) (° F). However, for heat transfer coefficients more than 35 Btu/(hr) (sq ft) (° F) the deviation between the actual and calculated is less than 30 per cent and this is within the accuracy of the methods for calculating theoretical heat transfer coefficients. (For example the Dittus and Boelter equation has a reliability of ± 20 per cent and most of the other equations for individual films have a larger uncertainty than this.)

Eight of the tests (No. 16, 19, 30, 31,

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32, 33, 34, and 37) had an absolute deviation greater than 11 Btu/(hr) (sq ft) (° F) and the least squares treatment indicated that these tests should be discarded; however, tests No. 19, 31, 32, 34, and 37 had a percentage deviation of less than 30 per cent which is within the accuracy of the method of calculation and therefore, were good tests even though the statistical treatment indicated otherwise. Tests 16 and 33 were believed to be in error due to the errors in the test data inasmuch as other tests on the same exchangers gave acceptable comparisons. When test No. 30 was made the condenser had been in service several years without cleaning and, therefore, was badly fouled on the water side. In addition, the unit was in such a service that foaming from the evaporating unit resulted in undue fouling on the condensing side.

The percentage deviations of the actual from the calculated coefficients were calculated and are shown in Tables 2-5. Except for the three tests, No. 16, 30, and 33, discarded as just mentioned, only five tests gave percentage deviations greater than 30 per cent and as expected these were all for heat transfer coefficiens below 30 Btu/(hr) (sq ft) (° F). The maximum percentage deviation obtained (exclusive of the discarded points) was 55 per cent.

● **Conclusions.** Commercial heat transfer coefficients can be calculated with engineering accuracy by methods available in the literature for the following types of exchangers:

1. Partial condenser.
2. Total condenser.
3. Liquid-liquid exchangers.
4. Gas exchangers.

for materials having the same fouling characteristics as water, chlorinated hydrocarbons, and low boiling hydrocarbons. For other systems, the coefficient can be calculated if the fouling factor is known; however, for systems with a high fouling factor, the coefficient cannot be predicted with high accuracy since the fouling film, which even at the best has a high uncertainty, may be the controlling film.

The overall heat transfer coefficient for reboilers (boiling liquid with condensing steam) cannot be calculated, mainly because the boiling film cannot be determined. For design purposes, a heat flux density of 8,000 to 10,000 Btu/(hr) (sq ft) (° F) at a temperature difference of 80 F seems to give conservative values for boiling chlorinated hydrocarbons, low boiling hydrocarbons and hydrochloric acid solutions.

● **Acknowledgment.** Many of the test data reported in Tables 2-6 were obtained by J. O. Davis, J. B. Jones, H. M. Rodekohr, T. M. Smylie, H. H. Wall, and W. R. Wilkinson. Assistance was obtained from R. Herzog in the statistical treatment of the data.

☆ ☆ ☆

Electronics are now used in laboratory work for the determination of properties and performance characteristics of aviation fuels.

● **Nomenclature**

A = area of heating surface, sq ft,
b = wetted perimeter, ft,
c_p = specific heat at constant pressure, Btu/(lb) (°F),
D = diamter, ft; D_e, equivalent diameter; D_2, outside diameter; D_1 and D_2, diameter of annulus,
F.C.S. = free cross-section open to flow,
G = mass velocity, lb/(hr) (sq ft of cross-section); $G_{max.}$ is the value based on the minimum area available for fluid flow; G_c refers to condensate; G_v to vapor,
h = coefficient of heat transfer, Btu/(hr) (sq ft) (°F); h_f is coefficient of a scale or deposit,
j = a product of dimensionless terms, $j = (h/c_pG)(c_p\mu/k)^{2/3}$,
k = thermal conductivity, Btu/(hr) (sq ft) (°F per ft),
L = thickness of exchanger tube, ft,
N.C.S. = net cross-section open to flow,
q = heat transferred, Btu/hr,
S = cross-section open to flow, sq ft,
T.R. = temperature range between inlet and outlet, ° F,
U = overall coefficient of heat transfer. Btu/(hr) (sq ft) (°F),
W = linear dimension of baffle, ft,
x = lateral dimension of baffle, ft,
y = distance between baffles, ft,
z = diagonal dimension between baffles, ft,
Δt = temperature difference, ° F; Δt_m is logarithmic mean temperature difference,
ρ = density, lb/cu ft,
ρ_l = density of liquid,
ρ_v = density of vapor,
μ = viscosity.

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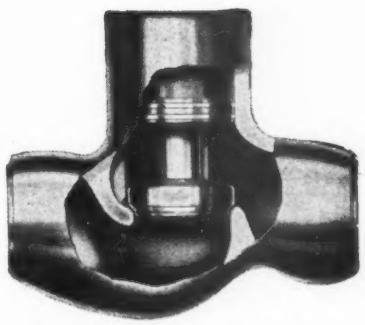

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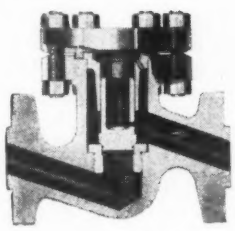

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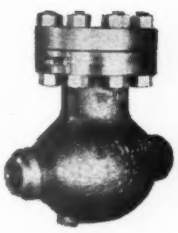

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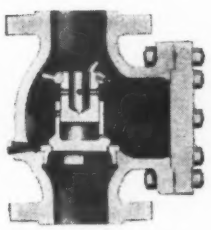

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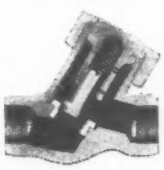

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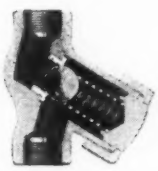

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Plate efficiency of fractionating columns and absorbers*

By H. E. O'CONNELL, Ethyl Corporation

● **Abstract.** A correlation of plate efficiency as a function of feed viscosity and the relative volatility of key components has been developed for fractionating towers from test data on 29 commercial columns and five laboratory columns previously reported in the literature and from new test data on three commercial columns not previously reported. Also, the correlation of Walter and Sherwood for laboratory plate absorbers, which expresses plate efficiency as a function of viscosity and Henry's law constant, has been simplified and compared with the efficiency for commercial absorbers. The correlations are suitable for determining the plate efficiency in the design of commercial fractionating columns and absorbers.

● **Introduction.** An important phase in the design of plate-fractionating columns and absorbers is the determination of the number of plates required in the column. The number of theoretical (or perfect) plates can be calculated by known methods[1, 2, 19, 20] but such a calculation involves the assumption that the vapor and liquid leaving the plate are in equilibrium. As this condition is rarely obtained, the number of theoretical plates must be divided by the plate efficiency in order to obtain the number of actual plates required.

Plate efficiency may be expressed in several ways.

1. Overall plate efficiency. This is the ratio of the number of equilibrium contacts (theoretical plates) to the number of actual plates.

2. Murphree plate efficiency. This expresses the efficiency for a single plate as follows:

$$E_{mv} = \frac{Y'_1 - Y'_o}{Y'_1 - Y'^*} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Where:

Y'_1 = mole fraction of more volatile component in the vapor phase of the total vapor entering the plate.

Y'_o = mole fraction of more volatile component in the vapor phase of the total vapor leaving the plate.

Y'^* = mole fraction of more volatile component in the vapor phase in equilibirum with the liquid leaving the plate.

3. Point efficiency. This is the efficiency at a single point on the plate.

The Murphree plate efficiency assumes that the liquid on each plate is completely mixed and that all the vapor comes in contact with liquid of the same composition as that leaving the plate. This is not the case because there is incomplete mixing of the liquid as it flows across the plate. Also, the vapor that passes through the caps near the inlet weir comes in contact with a liquid richer in the more volatile components than the liquid leaving the plate. Thus, it is possible to have a vapor leaving the plate richer in the more volatile component than the equilibrium concentration with the leaving liquid. For this case, Murphree plate efficiencies more than 100 per cent can be obtained.

The overall plate efficiency in most cases would fall between the Murphree plate efficiency and the local or point efficiency. The correlations presented in this paper are based on overall plate efficiencies. However, for some cases it was necessary to derive overall plate efficiency from Murphree plate efficiencies.

● **Factors affecting plate efficiency.** The plate efficiency of fractionating columns and absorbers is affected by both the mechanical design of the column and the physical properties of the solution.

Mechanical design. The following variables in mechanical design have been studied by others.

The vapor velocity in the column affects plate efficiency in that (as shown by Peavy and Baker[16]) the efficiency at low velocities increases with vapor velocity; at moderated velocities, remains constant for a considerable range; and then at high velocities, drops off as entrainment becomes pronounced. The optimum velocity for maximum plate efficiency can be obtained from the

TABLE 1. Plate efficiency of fractionation column.

Type of column	Lit. ref. no.	Symbol	Average column		Key components		α Rel. volatility	μ Viscosity of feed, average column conditions, centipoises	$\alpha\mu$	Plate eff., per cent
			Temp., F	Pressure, psia	High volatility	Low volatility				
1. Gasoline fractionator	3	0	197	215	Isobutane	Butane	1.36	0.10	0.14	74.0
2. Gasoline fractionator	3	0	217	265	Isobutane	Butane	1.31	0.09	0.12	88.0
3. Gasoline fractionator	3	0	200	218	Isobutane	Butane	1.28	0.10	0.13	86.0
4. Gasoline fractionator	3	0	205	223	Isobutane	Butane	1.28	0.10	0.13	83.0
5. Naphtha fractionator test 1	15	0	240	135	Isopentane	Pentane	1.21	0.15	0.18	63.0
6. Naphtha fractionator test 2	15	0	236	125	Isopentane	Pentane	1.21	0.16	0.19	69.0
7. Naphtha fractionator test 3	15	0	214	125	Butane	Pentane	2.20	0.15	0.33	67.4
8. Naphtha fractionator test 4	15	0	157	100	Butane	Pentane	2.61	0.22	0.57	51.0
9. Cracking unit stabilizer	8	0	315	347	Propane	Butane	1.76	0.07	0.13	84.0
10. Cracking unit stabilizer	8	0	309	363	Butane	Pentane	1.88	0.10	0.18	77.0
11. Cracking unit stabilizer	8	0	312	357	Propane	Butane	1.77	0.07	0.12	83.0
12. Cracking unit stabilizer	8	0	319	363	Propane	Butane	1.81	0.11	0.19	81.0
13. Cracking unit stabilizer	8	0	313	366	Propane	Butane	1.77	0.09	0.16	84.2
14. Cracking unit stabilizer	8	0	314	350	Propane	Butane	1.83	0.10	0.18	80.0
15. Poly plant stabilizer	8	0	198	362	Propane	Butane	2.11	0.22	0.47	55.0
16. Poly plant stabilizer	8	0	228	365	Propane	Butane	2.00	0.22	0.44	58.0
17. Butane depropanizer	8	0	162	235	Propane	Butane	2.45	0.15	0.36	68.0
18. Butane depropanizer	8	0	161	235	Propane	Butane	2.45	0.17	0.42	64.0
19. Debutanizer	8	0	275	117	Butane	Pentane	2.00	0.17	0.33	59.0
20. Deisopentanizer	8	0	280	116	Pentane	Hexane	1.90	0.16	0.30	64.0
21. Deisopentanizer	8	0	270	116	Pentane	Hexane	1.96	0.17	0.34	62.0
22. Deisopentanizer	8	0	262	116	Pentane	Hexane	1.98	0.16	0.31	67.7
23. Deisopentanizer	8	0	264	115	Pentane	Hexane	1.87	0.16	0.30	69.0
24. Deisopentanizer	8	0	260	117	Pentane	Hexane	1.97	0.15	0.30	73.0
25. Deisobutanizer	8	0	304	367	Isobutane	Butane	1.16	0.11	0.13	76.7
26. Deisopentanizer	8	0	253	98	Isopentane	Pentane	1.22	0.19	0.24	59.5
27. Stabilization of ethylene dichloride	22	Δ	206	21	Water	Ethylene Dichloride	20.51	0.37	7.60	29.0
28. Stabilization of ethylene dichloride*	22	Δ	220	28	Water	Ethylene Dichloride	16.0	0.35	5.60	29.0
29. Stabilization of ethylene dichloride*	22	Δ	220	28	Ethyl chloride	Ethylene Dichloride	3.1	0.35	1.08	57.0
30. Stabilization of ethyl chloride	22	Δ	173	151	Isobutane	Ethyl Chloride	1.69	0.11	0.19	85.0
31. Alcohol-water, lab. column	12	×	196	14.7	Ethyl alcohol	Water	9.03	0.32	2.89	32.0
32. Alcohol-water, lab. column	12	×	188	14.7	Ethyl alcohol	Water	7.05	0.36	2.54	47.0
33. Alcohol-water, lab. column	12	×	179	14.7	Ethyl alcohol	Water	2.34	0.42	0.98	77.0
34. Alcohol-water, lab. column	12	×	174	14.7	Ethyl alcohol	Water	1.27	0.45	0.57	62.0
35. Beer stills (perforated trays)	11	+	208	16	Ethyl alcohol	Water	10.8	0.32	3.46	41.0
36. Beer stills (perforated trays)	11	+	210	17	Ethyl alcohol	Water	10.8	0.32	3.46	42.5
37. Alcohol-water	17	+	200	15	Alcohol	Water	9.0	0.29	2.61	49.0
38. Trichloroethylene toluene and water, lab. column	18	□	210	15	Trichloro-ethylene	Toulene	2.12	0.30	0.635	53.0

*Results of one test with plate efficiency based on different components.

*First published in the August, 1946, Transactions of the American Institute of Chemical Engineers and reprinted by permission of the publishers.

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correlation of Brown and Souders[4] supplemented by the work of Brown and Lockhart.[3]

The plate efficiency of a column increases as the submergence of the slots is increased and is independent of slot velocity for the range of velocities commonly employed. This is shown by Carey et al.[6]

Adequate downcomer area and length must be provided to handle the liquid load and thus prevent column flooding. The method of calculation of downcomer size is summarized by Kirkbride.[13] In addition, for large diameter columns with high liquid loads, adequate provision must be made to insure plate stability. An unstable plate results when the liquid head at the entrance to the plate is considerably greater than the head at the discharge from the plate. With this condition, there is a tendency for the vapor to pass through only those caps with a low-liquid head. Good et al[10] have presented a correlation to determine the allowable liquid load in the column for stable plate operation.

The diameter of the column does not affect plate efficiency for diameters less than 5 ft. However, for columns larger than 7 ft, the length of the liquid path (cross flow effect) must be taken into account.

The methods just given are suitable for determining the optimum design of the mechanical features, both in regard to column operation and plate efficiency, within the range of column design currently used in practice.

Physical properties. The effect of physical properties of the solution on plate efficiency has not been studied as extensively as the mechanical-design features. Yet, the importance of physical properties has been shown by plate efficiencies varying from approximately 0 to 100 per cent in columns with similar mechanical designs. There have been only a few studies on the effect of physical properties on the plate efficiency.

Walter and Sherwood[23] conducted laboratory experiments on the absorption and desorption of carbon dioxide in water and glycerol solutions, the absorption of ammonia in water, and the absorption of hydrocarbons in oil. They showed that the plate efficiency increased with increasing solubility of the gas in the dissolving medium and with decreasing viscosity of the dissolving medium. Keyes and Byman[12] studied the system alcohol-water in a laboratory column and showed the effect of alcohol concentration on plate efficiency and indicated the effect of viscosity.

Gerster, Koffolt, and Withrow[9] showed that their $(PTU)_{ov}$, number of actual plates per number of transfer units, is a function of the slope of the equilibrium curve and the reflux ratio. For the special case where the number of transfer units is equal to the theoretical plates, it follows that the plate efficiency is a function of the slope of the equilibrium curve and the reflux ratio.

The most comprehensive study from a practical standpoint was made by Drickamer and Bradford[5] who showed that for commercial hydrocarbon fractionating columns and absorbers, the plate efficiency increased with decreasing viscosity. Drickamer and Bradford's correlation avoids the limitations of the other studies which were made in laboratory columns but has the disadvantage that it is suitable only for hydrocarbon separations with a low relative volatility of the key components.

The purpose of this investigation is to correlate plate efficiency with the physical properties of the material handled, the resulting correlation to be free of the limitations of the correlations mentioned. As a matter of convenience, separate correlations are presented for fractionating columns and absorbers, although the factors affecting both are in essence the same and could be presented in the same correlation.

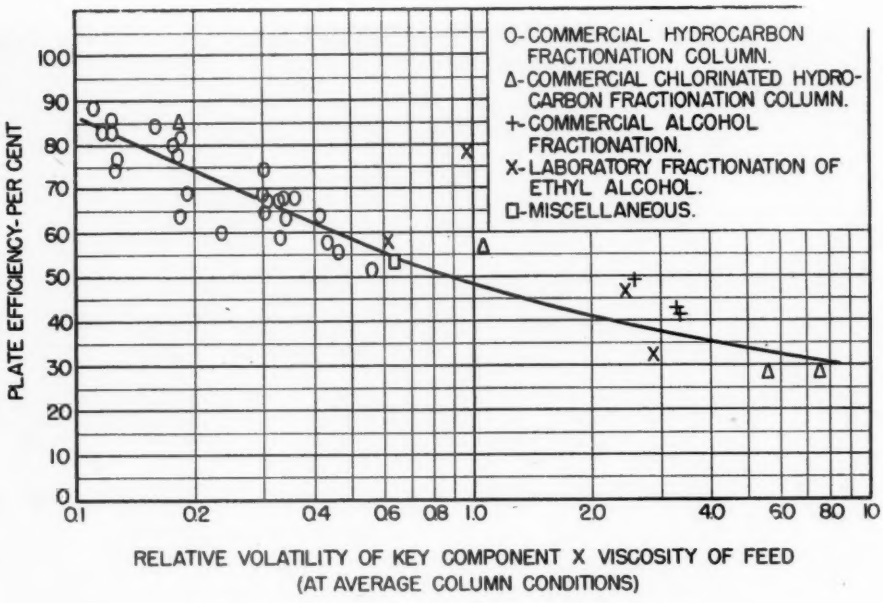
O-COMMERCIAL HYDROCARBON FRACTIONATION COLUMN.
Δ-COMMERCIAL CHLORINATED HYDROCARBON FRACTIONATION COLUMN.
+-COMMERCIAL ALCOHOL FRACTIONATION.
X-LABORATORY FRACTIONATION OF ETHYL ALCOHOL.
□-MISCELLANEOUS.
PLATE EFFICIENCY-PER CENT
RELATIVE VOLATILITY OF KEY COMPONENT X VISCOSITY OF FEED
(AT AVERAGE COLUMN CONDITIONS)

FIG. 1. Effect of relative volatility and viscosity on plate efficiency of fractionating columns.

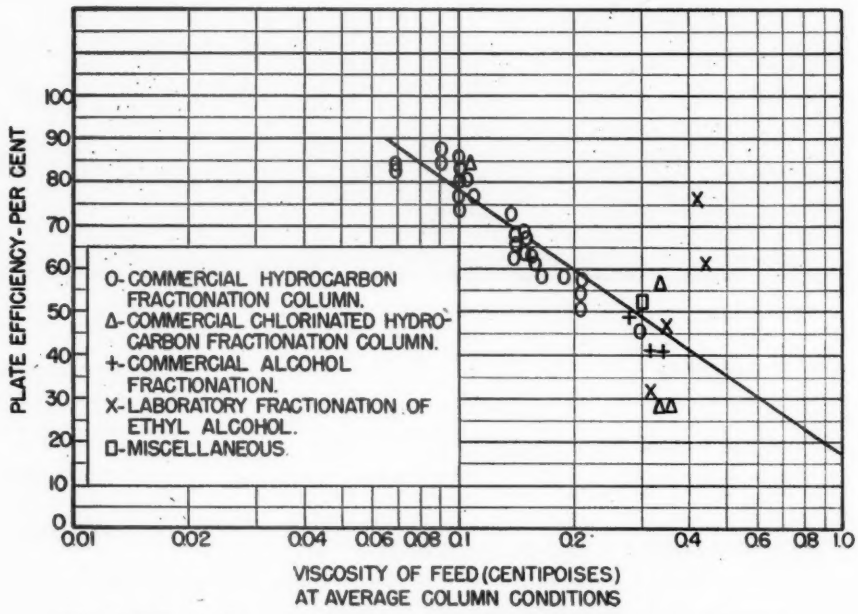

FIG. 2. Effect of viscosity on plate efficiency of fractionating columns.

● **Plate efficiency of fractionating columns.** The plate efficiency of fractionating columns was correlated (Fig. 1) as a function of the product of the relative volatility of the key components* and the average molal liquid viscosity (in centipoises) of the column feed, both at the average tower temperature and pres-

*Key components are those for which definite limiting concentrations have been specified in the overhead and bottoms.

TABLE 2. Plate efficiency of absorbers.

Type of column	Lit. ref. no.	Symbol	Average column		Key component	HP*	μ Liquid viscosity, centipoises	HP/μ	Plate eff., per cent
			Temp., F.	Pressure, psia					
1. Poly plant absorber	8	A	127	260	Butane	0.85	0.41	2.07	39.0
2. Poly plant absorber	8	A	124	265	Butane	0.94	0.50	1.96	38.0
3. Poly plant absorber	8	A	126	255	Butane	0.78	0.41	1.94	42.0
4. Poly plant absorber	8	A	120	260	Butane	0.87	0.48	1.76	36.0
5. Absorber	8	A	132	254	Butane	0.96	0.31	3.10	50.0
6. Absorber	8	A	138	267	Butane	0.92	0.22	4.13	56.4
7. Absorber	8	A	117	94	Butane	0.32	1.41	0.22	10.4
8. Absorber	5	A	93	485	Isopentane	5.16	0.42	12.28	50.0
9. Cracking coil gas absorber†	19	A	60	92	Ethylene	0.04	1.90	0.02	10.3
10. Cracking coil gas absorber†	19	A	60	92	Ethane	0.06	1.90	0.03	14.9
11. Cracking coil gas absorber†	19	A	60	92	Propylene	0.20	1.90	0.11	25.5
12. Cracking coil gas absorber†	19	A	60	92	Propane	0.22	1.90	0.11	26.8
13. Cracking coil gas absorber†	19	A	60	92	Butylene	0.61	1.90	0.32	33.8
14. Absorption of propylene in heavy naphtha in a 2-in. column	23	C	75.2	66	Propylene	0.15	1.00	0.15	24.0
15. Absorption of propylene in heavy naphtha in a 2 in. column	23	C	109.4	66	Propylene	0.10	0.74	0.13	21.6
16. Absorption of propylene in heavy naphtha in a 2-in. column	23	C	69.8	46	Propylene	0.12	1.05	0.10	22.6
17. Absorption of isobutylene in heavy naphtha in a 2-in. column	23	C	78.8	66	Isobutylene	0.54	0.97	0.56	36.4
18. Absorption of propylene in gas oil in a 2-in. column	23	C	75.2	66	Propylene	0.12	5.50	0.02	11.0
19. Absorption of propylene in gas oil in a 2-in. column	23	C	118.4	66	Propylene	0.07	2.80	0.03	13.1
20. Absorption of isobutylene in gas oil in a 2-in. column	23	C	77.0	66	Isobutylene	0.39	5.40	0.07	17.4
21. Absorption of isobutylene in gas oil in a 2-in. column	23	C	86.0	66	Isobutylene	0.33	4.80	0.07	17.1
22. Absorption of isobutylene in gas oil in a 2-in. column	23	C	98.6	66	Isobutylene	0.27	3.90	0.07	17.6
23. Absorption of propylene in gas lube oil in a 2-in column	23	C	73.4	66	Propylene	0.08	21.50	0.004	10.6
24. Absorption of propylene in gas lube oil in a 2-in. column	23	C	105.8	66	Propylene	0.05	10.50	0.005	4.7
25. Absorption of isobutylene in gas lube oil in a 2-in. column	23	C	75.2	66	Isobutylene	0.32	20.60	0.02	10.1
26. Absorption of isobutylene in gas lube oil in a 2-in. column	23	C	75.2	66	Isobutylene	0.32	20.60	0.02	9.2
27. Absorption of carbon dioxide in water in an 18-in. column (avg. of 7 runs)	23	B	50.4	14.7	Carbon dioxide	0.003	1.30	0.002	2.0
28. Desorption of carbon dioxide in water in a 5-in. column (avg. of 32 runs)	23	B	78.6	14.7	Carbon dioxide	0.002	0.88	0.002	2.4
29. Desorption of carbon dioxide in 12.2 weight per cent glycerol in a 5-in. column	23	B	77.0	14.7	Carbon dioxide	0.002	1.21	0.002	1.6
30. Desorption of carbon dioxide in 23.6 weight per cent glycerol in a 5-in. column	23	B	77.0	14.7	Carbon dioxide	0.002	1.71	0.001	0.96
31. Desorption of carbon dioxide in 33.2 weight per cent glycerol in a 5-in. column	23	B	77.0	14.7	Carbon dioxide	0.001	2.36	0.0004	0.96
32. Desorption of carbon dioxide in 43.7 weight per cent glycerol in a 5-in. column	23	B	77.0	14.7	Carbon dioxide	0.001	3.74	0.0003	0.65
33. Absorption of ammonia in water	23	D	57.0	14.7	Ammonia	5.80	1.17	4.96	69.0

*HP = $\frac{\text{sp. gr. of liquid in lb/cu ft}}{\text{equilibrium vaporization constant of key component} \times \text{molecular weight of liquid}}$

†Results of one test with plate efficiency based on different components.

sure. The data for the correlations were obtained from tests reported in the literature on 29 commercial columns and five laboratory columns and from three unpublished tests on commercial columns. The data for all the tests are summarized in Table 1. Complete data for the unpublished tests are presented in Table 3.

Efficiencies for all tests were overall plate efficiencies and for most of the tests these were readily obtainable; however, for the laboratory tests on the alcohol-water column,[12] tests 31 to 34 in Table 1, the overall plate efficiency was obtained by assuming it to be between the reported Murphree and point efficiencies. This appears to be a reasonable assumption since these efficiencies compare favorably with overall plate efficiencies obtained in a commercial fractionation column with ethyl alcohol. Other laboratory data, for example the work of Peavy and Baker[16] on ethyl alcohol-water system, were not included because the Murphree plate efficiencies reported could not be translated to overall plate efficiencies.

Viscosity and relative volatility were selected as the most important physical properties affecting plate efficiency for the following reasons:

1. The effect of viscosity on plate efficiency has been shown by Drickamer and Bradford, who presented a correlation of plate efficiency with viscosity for hydrocarbon separations of about the same relative volatility. This is a logical relationship, inasmuch as the mass transfer of vapors and liquids is a function of viscosity as shown by Chilton and Colburn[7] and Walter and Sherwood.[23]

2. The effect of relative volatility was shown by the results of a test on an ethylene dichloride stabilizer. (Table 3). In this column, the feed contained both water and ethyl chloride which had to be reduced to low concentrations in the ethylene dichloride bottoms. The plate efficiency based on water as the low-boiling key component (ethylene dichloride the high-boiling key component) was 29 per cent and the relative volatility between water and ethylene dichloride was 16. The plate efficiency based on ethyl chloride as the low-boiling key component was 57 per cent and the relative volatility between ethyl choloride and ethylene dichloride was 3.1. No theoretical explanation for this relationship has been found.

The agreement between test results (Table 1) and the fitted curve for these data (Fig. 1) was good. Average deviation was ± 10 per cent and 90 per cent of the data fell within ± 16 per cent of the predicted curve. Only one point, obtained from a laboratory test on an ethyl alcohol-water separation, deviated more than 30 per cent from the curve and was believed to be in error. The deviations from the curve are to be expected from errors in analyses, inaccuracies in physical data, and limitations in the method of calculation. In addition, differences in column design could account for some of the deviation.

The plate efficiency was plotted against the viscosity of the feed in Fig. 2, as suggested by Drickamer and Bradford. This gave practically as good an agreement between actual and predicted efficiency as obtained in Fig. 1. This is to be expected because most of the tests are for systems of similar relative volatilities. however, for the tests where the relative volatility is high (Points +, ×, and △ on Figs. 1 and 2), this paper (Fig. 1) gave a better correlation.

● **Plate efficiency of absorbers.** The plate efficiency of absorbers was correlated (Fig. 3) as a function of the term HP/μ

Where:

H = Henry's law constant in lb moles per (cu ft) (atm),

P = pressure in atm,

μ = viscosity of absorbent in centipoises.

All values are taken at average column conditions.

The data were obtained from tests reported in the literature on 13 commercial columns and 20 laboratory columns. These data are summarized in Table 2.

The efficiencies for the commercial absorbers were overall plate efficiencies, but, unfortunately the efficiencies for the laboratory columns were Murphree plate efficiencies; however, it was assumed that the Murphree plate efficiencies were equal to the overall plate efficiencies. This assumption was based on:

1. Data on absorption of hydrocarbons in oil in the laboratory columns gave Murphree efficiencies equal to the overall plate efficiencies obtained in commercial columns for similar systems.

2. The laboratory data were obtained in small columns where there is little difference in the Murphree plate efficiency and point efficiency. For this condition, the Murphree plate efficiency most likely approaches that of the overall plate efficiency. However, two of the tests were run in an 18-in. column and one of the tests, the absorption of ammonia in water, gave a Murphree plate

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efficiency of 69 per cent, which was higher than the overall plate efficiency predicted in Fig. 3. This was expected since Murphree plate efficiencies are usually larger than overall plate efficiencies in large columns.

This correlation is similar to one presented by Walter and Sherwood who correlated the results on the laboratory column tests reported in Table 2, and is based on the same concepts used in the fractionating column correlation. Actually both correlations (Figs. 1 and 3) could be presented on the same figure, but the difficulty of expressing the solubility effect on the same basis made it more desirable to present two plots.

The average deviation between predicted efficiency in the curve of Fig. 3 and actual efficiency was ± 9 per cent if the points (C) and HP/μ of 0.004 and plate efficiency of 10 per cent and (A) at HP/μ of 0.22 and plate efficiency of 10 per cent are excluded. These were the only two points where the deviation was greater than 20 per cent.

The plate efficiency was plotted against viscosity in Fig. 4. The points scattered widely showing the pronounced effect of material solubility on plate efficiency. The line on the graph is that presented by Drickamer and Bradford for commercial hydrocarbon fractionating columns and absorbers.

● **Effect of tray design and reflux ratio on plate efficiency.** The results of this study show that, with present design methods, the variance in column design found in commercial columns does not affect plate efficiency appreciably. This does not imply that improvement in column design cannot be realized, but on the contrary, shows that in some cases present design methods are not adequate to realize the full potentialities of the concept of a theoretical plate. Therefore, a study of tray design should be made with the purpose of obtaining a design that will overcome the deleterious effect of high viscosity and high relative volatility on plate efficiency.

The correlations presented in this memorandum do not show any effect of reflux ratio on plate efficiency and this is to be expected if the column is operated at the optimum vapor and liquid loads; however, Gerster, Koffolt, and Withrow[9] showed that the relationship $(PTU)_{ov}$, number of actual plates equivalent to a transfer unit, is a function of the reflux ratio as well as the slope of the equilibrium curve. When the number of transfer units equals the number of theoretical plates, $(PTU)_{ov}$ is the inverse of the plate efficiency. This is a special condition that is not always met.

● **Summary.** Correlations have been presented for predicting overall plate efficiencies of commercial fractionating columns and absorbers within the accuracy of the other variables in design (tray design, physical-property data, and method of calculation). The correlations are semi-empirical and therefore have all the limitations of empirical relationship and should be used as such. A wide diversity of systems was used. For the fractionation column, correlation data were available on hydrocarbon, chlorinated hydrocarbon, alcohol-water and trichloroethylene-toluene-water systems. For the absorber correlation, data were available on the laboratory desorption of carbon dioxide from water and glycerol solution, the absorption of ammonia in water and the absorption of hydrocarbons in oil in both commercial and laboratory columns. Overall plate efficiencies (as defined above) were used although in some cases it was necessary to derive the overall plate efficiencies from Murphree plate and point efficiencies. This latter point should not be considered a limitation of the correlation because such data could be omitted from the correlations without an appreciable impairment of their value.

The determination of the number of theoretical plates requires accurate vapor-liquid equilibria data. In many cases, especially in multicomponent mixtures such data are not available and are difficult to obtain. For example, the equilibrium vaporization constant ($K = y/x$) which are available for hydrocarbons are in some cases a function of the composition of the liquid and the critical properties of the mixture as well as the temperature and pressure of the system.

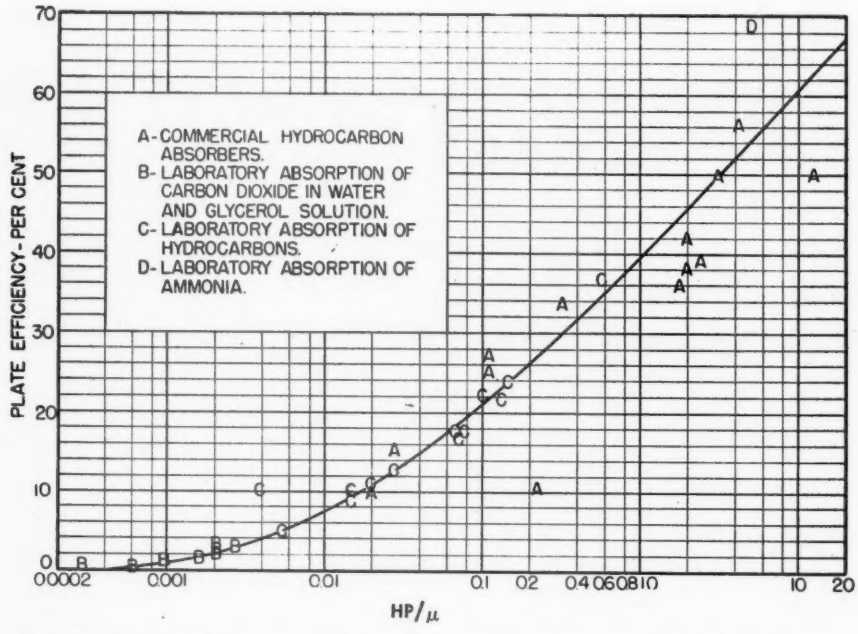
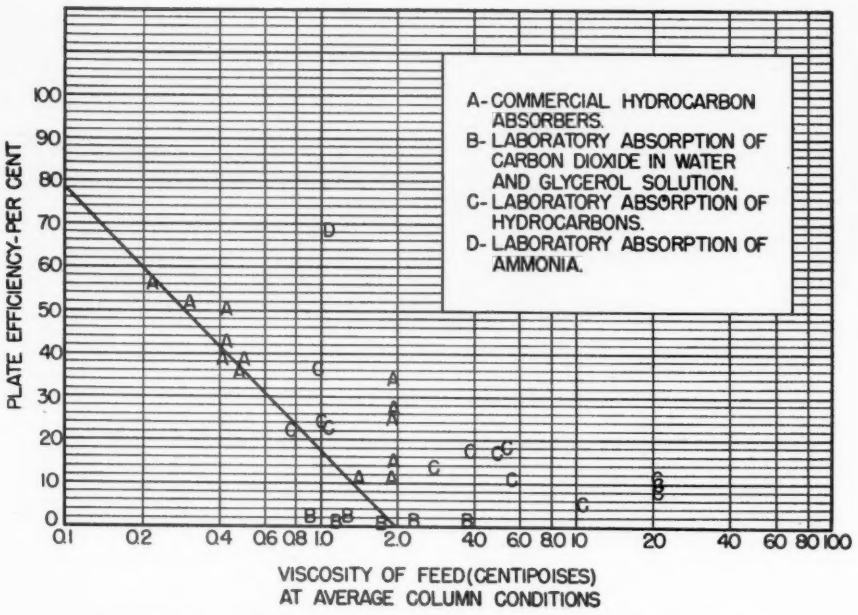

A- COMMERCIAL HYDROCARBON ABSORBERS.
B- LABORATORY ABSORPTION OF CARBON DIOXIDE IN WATER AND GLYCEROL SOLUTION.
C- LABORATORY ABSORPTION OF HYDROCARBONS.
D- LABORATORY ABSORPTION OF AMMONIA.
PLATE EFFICIENCY-PER CENT
HP/μ

FIG. 3. Effect of solubility and viscosity on plate efficiency of plate absorbers.


A- COMMERCIAL HYDROCARBON ABSORBERS.
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C- LABORATORY ABSORPTION OF HYDROCARBONS.
D- LABORATORY ABSORPTION OF AMMONIA.
PLATE EFFICIENCY-PER CENT
VISCOSITY OF FEED(CENTIPOISES) AT AVERAGE COLUMN CONDITIONS

FIG. 4. Effect of viscosity on plate efficiency of plate absorbers.

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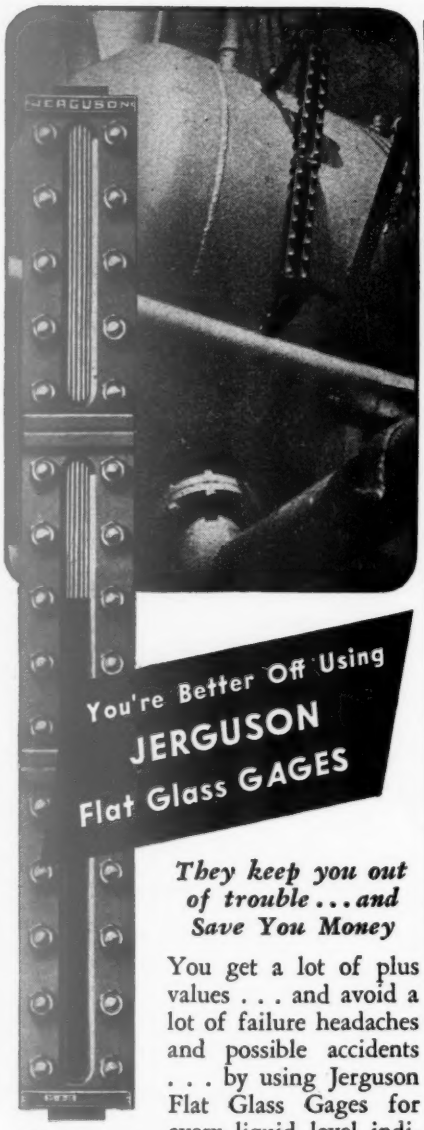

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TABLE 3.

Tests conducted at Ethyl Corporation, Baton Rouge, Louisiana.

Test No. 1

Stabilization of ethylene dichloride

Number of plates	7
Plate spacing	18 in.
Column diameter	30 in.
Feed plate	top plate
Feed flow	90.7 moles/hr
Overhead flow	35.6 moles/hr
Bottoms flow	55.1 moles/hr
Feed temperature	116 F
Top temperature	214 F
Bottom temperature	230 F
Column pressure	27.5 psia
Heat supplied in reboiler	808,000 Btu/hr
Heat removed in overhead condenser	570,000 Btu/hr

Component	Feed*	Bottoms*	Overhead*
Ethane	0.0188	.....	0.0300
Ethyl chloride	0.0157	0.0001	0.0400
Water	0.0138	0.0003	0.0346
Ethylene dichloride	0.9504	0.9975	0.8949
Trichloroethane	0.0013	0.0021	0.0005

*Mole fraction.

Theoretical plates required for water-ethylene dichloride separation†	2
Plate efficiency for water-ethylene dichloride separation (2/7) (100), per cent	29
Theoretical plates required for ehtyl chloride-ethylene dichloride separation†	4
Plate efficiency for ethyl chloride-ethylene dichloride separation (4/7) (100), per cent	57

†Calculated by method of Sorel.[20] Equilibria data for systems water-ethylene dichloride and ethyl chloride-ethylene dichloride obtained from unpublished data from Ethyl Corporation.

Test No. 2

Stabilization of ethylene dichloride

Number of plates	7
Plate spacing	21 in.
Column diameter	24 in.
Feed plate	top plate
Feed flow	76.3 moles/hr
Overhead flow	22.1 moles/hr
Bottoms flow	54.2 moles/hr
Feed temperature	57 F
Top temperature	189 F
Bottom temperature	207 F
Column pressure	6 psig
Heat supplied in reboiler	708,000 Btu/hr
Heat removed in overhead condenser	328,990 Btu/hr

Component	Feed*	Bottoms*	Overhead*
Water	0.0065	0.0001	0.0221
Ethylene dichloride	0.9935	0.9999	0.9779

*Mole fraction.

Theoretical number of plates required for separation	2
Plate efficiency (2/7) (100), per cent	29

Test No. 3

Stabilization of ethylene dichloride

Number of plates	24
Plate spacing	18 in.
Column diameter	30 in.
Feed plate	top plate
Feed flow	196.7 moles/hr
Overhead flow	86.1 moles/hr
Bottoms flow	110.6 moles/hr
Feed temperature	—24 F
Top temperature	142 F
Bottom temperature	203 F
Column pressure	136 psig
Heat supplied in reboiler	1,600,000 Btu/hr
No overhead condenser	

Component	Feed*	Bottoms*	Overhead*
More volatile than isobutane	0.1901	<0.00001	0.4342
Isobutane	0.0593	0.001	0.1354
Ethyl chloride	0.7506	0.999	0.4304

*Mole fraction.

Number of theoretical plates required for separation isobutane-ethyl chloride†	20.5
Plate efficiency (20.5)/(24) (100), per cent	85

†Equilibria data for system isobutane-ethyl chloride obtained from unpublished data from Ethyl Corporation.

Such factors must be taken into account in the calculation of the number of theoretical plates required.

● **Acknowledgment.** The test data in Table 3 were obtained by E. P. Breidenbach, H. M. Rodekohr, T. M. Smylie, H. H. Wall, and P. R. Walton of the development section of Ethyl Corporation. The data were compiled and the graphs prepared by Rose E. Worsham. The author wishes to acknowledge with thanks the critical review of the report by O. E. Kurt, F. A. McCoy and F. J. Sergeys.

● **Nomenclature.**

μ = viscosity, centipoises,

H = Henry's law constant in lb moles per cu ft atm,

P = pressure in atmospheres,

α = relative volatility,

$(PTU)_{ov}$ = number of plates equivalent to a transfer unit,

E = overall plate efficiency,

E_{mv} = Murphree plate efficiency = $Y'_1 - Y'_o / Y'_1 - Y'^*$,

E_{pv} = point plate efficiency,

Y'_1 = mole fraction of more volatile component in the vapor phase of the total vapor entering the plate,

Y'_o = mole fraction of more volatile component in the vapor phase of the total vapor leaving the plate,

Y'^* = mole fraction of more volatile component in the vapor phase in equilibrium with the liquid leaving the plate.

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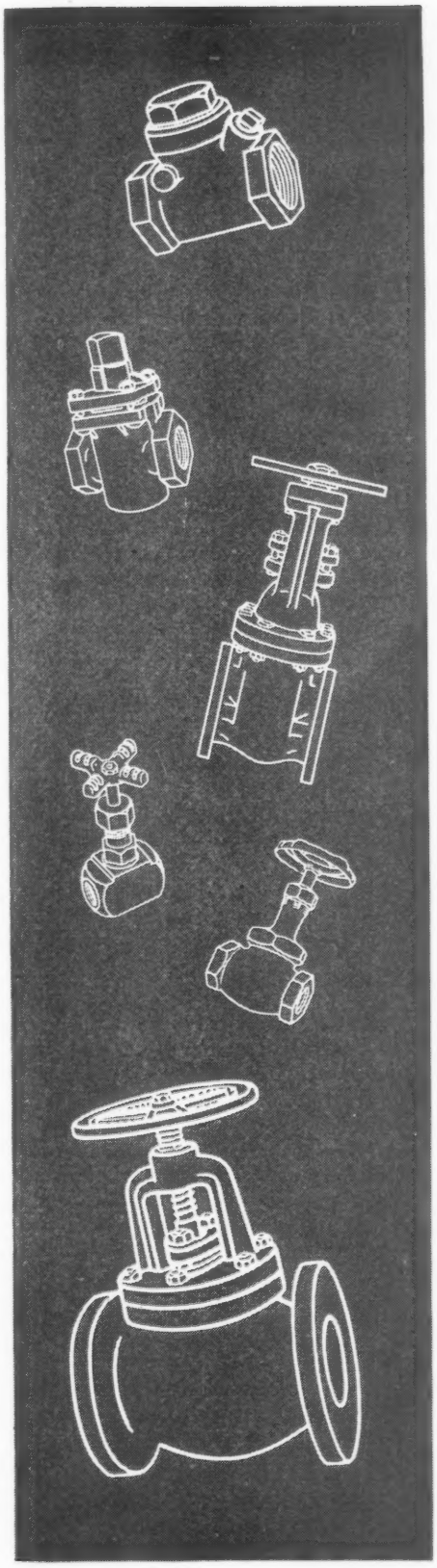

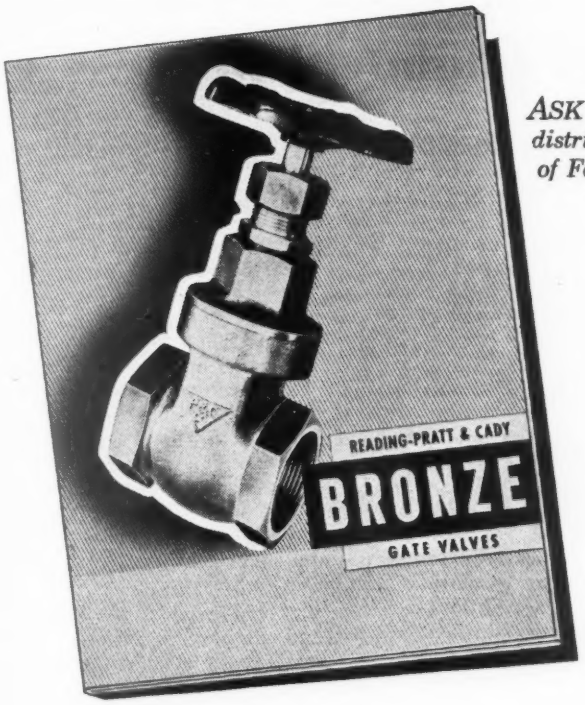

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Some case histories of corrosion problems in chemical process equipment*

By W. Z. FRIEND† and F. L. LaQUE†, International Nickel Company, Inc.

In corrosion engineering, as in most other activities, much of our progress is made by a careful study of the mistakes, or rather the unfortunate experiences of ourselves or others. From an accumulation of such experiences, backed up by fundamental research, has come a pretty good understanding of the principal factors that affect corrosion. The proper application of this knowledge to preliminary laboratory, pilot plant, or full plant corrosion tests usually leads to the selection of suitable corrosion-resistant materials and to the proper methods of operation of process equipment to avoid corrosion. Occasionally, a case of unexpectedly high corrosion occurs in which a considerable amount of diligent test work may be required to find the cause of the trouble.

A study of cases involving corrosion of chemical process equipment reveals that in most of them, unexpected corrosion was due to a failure to recognize the presence of, or anticipate the effects of, one or more of the following factors:

Aeration or lack of aeration.

Temperature of solution or metal.

Velocity or agitation.

Presence of minor but highly corrosive constituents.

Presence of a constituent (in solution or suspension) that destroyed the protective films.

Absence of a constituent expected to inhibit corrosion.

Unfortunate combinations of metals with unfavorable area relationships that lead to galvanic corrosion.

Concentration cells responsible for localized corrosion.

Improper heat treatment or other conditioning of the metal.

Histories of investigation of a number of cases of corrosion of plant equipment are given to illustrate the methods of attack sometimes required to solve such problems. These cases have been selected to illustrate the effects of one or more of the corrosion factors, and not with the idea of covering a range of metals and alloys.

● **Case 1. Effect of aeration on reduction of dyestuff.** The problem was to determine why a different percentage of a certain dyestuff (sulphon cyanine black B) was required in different dyeing machines in the same plant, to produce the same shade on stockings knitted from the same batch of silk when they were degummed and dyed by the one-bath method. The dyeing was done in standard rotary hosiery dyeing machines made of monel and containing bronze gears and nickel silver heating pipes. There were six of these machines in the same service. No. 1 machine of 100-lb capacity was the most reliable and was being used for the bulk of the dyeing. No. 4, a 50-lb machine, was thoroughly unstable and usually required indefinite additions of black.

It was contended by the suppliers of dyes and other processing chemicals that the metals in the machines were responsible in some way for the difficulty. This was eventually proved to be wrong but the contention did lead to a thorough investigation, which established that variations in amounts of dissolved air in the dyebaths in the different machines, and particularly deficiency of air in certain machines, were the elusive factors responsible for the difficulty.

The first step in the investigation was to make laboratory dyeings in open porcelain beakers with and without the presence of monel, bronze, and nickel silver test pieces, both alone in galvanic contact with each other. Care was taken in all tests to insure that the weight of goods, volume of liquid, and area of metal test piece were in the same relationship as in the dyeing machines; also that the percentages of various ingredients, temperature and other factors incidental to the dyeing process were maintained properly. Parallel dyeings were made on previously degummed silk; also dyeings by the customary one-bath process. The colors were all good with no difference in shade. These tests indicated clearly that the metals did not affect the color but they failed to show what did.

The scene of activities was then shifted to the dyehouse. It was shown repeatedly that, when the batch was degummed first and then dyed in a fresh bath with the degumming agents present, uniformly good color was obtained in all machines. This indicated that the difficulty was associated with the presence of serecin, or silk gum.

There followed a considerable number of laboratory experiments, this time made in one-liter wide-mouth Erlenmeyer flasks equipped with reflux condensers, in which various factors were studied including the presence of metals. The principal conclusions were:

1. Reduction of dyestuff was obtained whenever serecin was present and the temperature and pH conditions were the same as in the dyehouse.

2. This reduction was obtained in glass equipment in the absence of any metals.

In comparing these tests with the earlier laboratory tests, it became apparent that the principal difference was in the amount of aeration. In the first case, dyeings were made in open beakers under conditions insuring a high degree of aeration, while in the other case, the arrangement and operation of the apparatus was such that free access of air was prevented. The final step was to apply this knowledge to the operation of the dyehouse machines.

In No. 1 machine (which had never given any trouble) it was possible repeatedly to get considerable reduction of the dyestuff by stopping the rotation of the cylinder for as short a time as 10 min. In No. 4 machine (which had previously given trouble) air was injected into the solution through one of the perforated steam pipes, and perfect colors were obtained. In later experiments it was found that only a very small amount of air was required to prevent reduction of the dyestuff by the serecin. It was apparent finally that the effective differences in the various machines were in the degrees of tightness of covers and doors and possibly in the breathing action of the rotating cylinders in the machines of different sizes.

● **Case 2. Effect of corrosive impurities in caustic soda.** This case involved the abnormally high corrosion rate of nickel tubes in a continuous forced-circulation nickel evaporator operating under 28 in. Hg vacuum and used for concentrating lime-soda caustic soda from 50 per cent to 70-75 per cent concentration. Steam was at approximately 265 F under 70 psig pressure. The evaporator was equipped with 208 tubes, each ⅞ in. OD by 16 gauge by 10 ft long. Examination of 12 typical tubes after eight months' service showed an average weight loss of 2 lb per tube. This was equivalent to an average corrosion rate of 190 mdd or 0.031 ipy, based on continuous operation. This corrosion rate was more than ten times that normally experienced in the tubes of forced-circulation nickel evaporators handling caustic of similar concentrations.

Examination of the inside surface of a number of the tubes showed them to be covered with a black film, which analysis showed to be principally nickel sulphide. This led to the conclusion that the caustic in this plant was unusually high in sulphur compounds, confirmed by analy-

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†Both authors are in corrosion engineering section, development and research division, International Nickel Company, Inc.

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ses to be as high as 0.0098 per cent calculated as H_2S based on the weight of solid caustic. Possible sources of sulphur compounds appeared to be: Re-use of "bottoms" from caustic fusion pots in which sulphur shading was used; burning of sulphur-containing natural gas in lime kilns; perhaps other additions for specific treating purposes

In caustic of high concentration, the resistance of nickel to attack depends to a considerable degree on the formation of a protective nickel oxide coating. It seemed possible that if certain sulphur compounds were present in the caustic, the formation of sulphides might prevent the development of a proper oxide coating with the result that corrosion would be increased.

Corrosion tests were made in the evaporator by placing specimens of nickel immediately above the top tube sheet where they would be subject to the velocity of liquor emerging from the tubes. In 24-day tests, the average corrosion rate of five specimens of nickel was 132 mdd (0.021 ipy). Allowing for difference in velocity this was in good agreement with the corrosion rate of tubes. Similar tests in another plant during concentration of electrolytic caustic soda had shown an average corrosion rate of 10 mdd (0.0016 ipy) for nickel.

In order to observe the corrosive effects toward nickel of different sulphur compounds laboratory tests were made in 75 per cent C.P. caustic at 265 F with and without the addition of 1 per cent of the sulphur compounds shown in Table 1. Duration of these tests was 20 hr. They confirmed the suspicion that certain oxidizable sulphur compounds could accelerate the corrosion of nickel by caustic soda to the extent observed in the plant.

Further tests showed that, by addition to the plant caustic liquor, of sufficient sodium peroxide to oxidize all of these compounds to sodium sulphate, corrosion of nickel was reduced to a suitable low figure. In this case the most economical solution was to eliminate the sources of oxidizable sulphur compounds.

● **Case 3. Effects of a combination of factors.** Another case involved the abnormal corrosion of nickel tubes in a forced-circulation evaporator used to concentrate electrolytic caustic soda to 50 per cent concentration. In this case, the evaporator operated under 5 psi pressure with the liquor temperature at approximately 300 F and with steam at 120 to 135 psi or about 350 F. The evaporator was equipped with 416 nickel tubes, each 7/8 in. OD by 16 gauge by 10 ft long. The caustic solution circulating through the tubes contained approximately 5 per cent crystalline salt in suspension. By weighing 43 tubes removed from the evaporator it was found that the average weight loss corresponded to an average corrosion rate of 118 mdd (0.019 ipy). These tubes were all corroded somewhat more at the top and bottom ends due to turbulence effects. The average corrosion rate of the least corroded middle sections was 106 mdd (0.017 ipy). Failure in most cases had occurred near the top tube sheet where the tube walls had been somewhat thinned by the end of the tube roller. These corrosion rates were several times those normally expected in the evaporation of caustic to 50 per cent.

TABLE 1. Corrosion of nickel by C.P. 75 per cent caustic soda containing added sulphur compounds.

Temperature: 265 F Duration of tests: 20 hr

Addition agent	Average corrosion rate	
	mdd	ipy
1 per cent sodium sulfide	141	0.023
1 per cent sodium thiosulphate	49	0.008
1 per cent sodium sulphite	32	0.005
1 per cent sodium sulphate	4	0.0007
None	3.5	0.0006

In a preliminary study of the problem, there appeared to be the following significant differences in the operation of this evaporator and those at most other plants:

1. The operating temperature was higher. Similar evaporators normally operate under vacuum at about 200 F.
2. The amount of entrained salt was higher than usual.
3. It had been the practice to add some chlorine to the cell feed liquor that might be expected to make the amount of available chlorine in the caustic somewhat higher than normal.

Previous experience had shown no significant difference in corrosion rates of nickel in pure 50 per cent caustic at 200 F and 300 F so it was felt that temperature alone could not be a signicant factor; however, there was the possibility that this combination of temperature and entrained salt content would be effective in removing the protective oxide film from nickel. Liquor velocity entering the tubes was calculated to be about 9.5 fps, with some unknown higher velocities at the outlet end due to steam liberation. The inside surfaces of the tubes were roughened more than usual, indicating abrasion as a factor.

In an attempt to study the effects of temperature, velocity, and salt content a series of laboratory tests was undertaken in samples of plant caustic as well as synthetic caustic soda-salt mixtures made up with CP caustic. The sample of plant caustic, as received, contained 100 ppm oxidizing material calculating as available chlorine but did not contain oxidizable sulphur compounds. The test results were erratic, due chiefly to inability to keep all the crystalline salt in suspension, and corrosion rates were in general less than those observed in the plant.

In order more clearly to duplicate plant condiitons, all-nickel test equipment was set up in the plant, next to the evaporator so that liquor could be pumped directly from the evaporator through the test equipment, and back into the evaporator. Steam jacketed 1-in. ips nickel tubes 10 in. long were used as test pieces. Tests were made at various tube velocities ranging from 3 to 14 fps and at various temperatures. With this equipment, when operating at the same liquor and steam temperatures and velocity as in the evaporator it was possible to duplicate the corrosion rates shown by the evaporator tubes. The effect of velocity on corrosion rate is shown below.

Velocity, fps	Avg corrosion rate, mdd
2-3	68
5	86
9-10	110
13-14	114

When steam was omitted from the steam jacket, and liquor from the evaporator at 300 F was circulated through the test unit at 13-14 fps velocity, the corrosion rate was reduced to an average of 64 mdd showing the important effect of high tube wall temperature in increasing corrosion where as much as 5 per cent entrained salt was present.

Subsequent tests were made at lower temperatures and with smaller amounts of entrained salt present in the caustic. With entrained salt in the neighborhood of 1 per cent, liquor velocities of 9-10 fps, and with steam temperatures controlled to be the same as liquid temperatures, the following corrosion rates were obtained at various temperatures:

Temp. F	Corrosion rate, mdd
285	23.4
265	17.2
212	16.6

These rates corresponded with those obtained normally for the tubes in 50 per cent caustic evaporators in other plants. They confirmed the fact that the high corrosion rates of tubes had been due to the high entrained salt content of the caustic combined with the unusually high tube wall temperatures. Subsequent changes in operation including reduction of the amount of available chlorine present in the caustic increased evaporator tube life to a satisfactory point.

● **Case 4. Effect of carbon dioxide in steam.** Another case involving the unexpected corrosion of nickel tubes, occurred almost simultaneously in caustic soda evaporators at two different plants, but in these cases on the steam side of the tubes rather than on the caustic side. In both cases the only evaporators in which this corrosion occurred were the first effects of multi-effect evaporator systems. They were heated with plant steam whereas the other effects were heated with process steam evaporated from the first effects. Corrosion of the tubes had occurred at random with some tubes not attacked and with no observed relationship to the construction of the evaporator. In Plant A the first effect operated with 35 psi steam pressure, and in Plant B with 10 psi steam.

It seemed likely that corrosion could be due only to non-condensables dissolved in the condensate from the plant steam, although this had not been encountered previously with nickel. Analyses of the non-condensable gases from the steam side of the first-effect evaporators were made at both plants. In Plant A, ten samplings throughout a year showed the carbon dioxide content to vary from 20 to 87 per cent by volume with an average of 64 per cent. Oxygen

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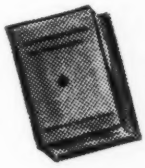

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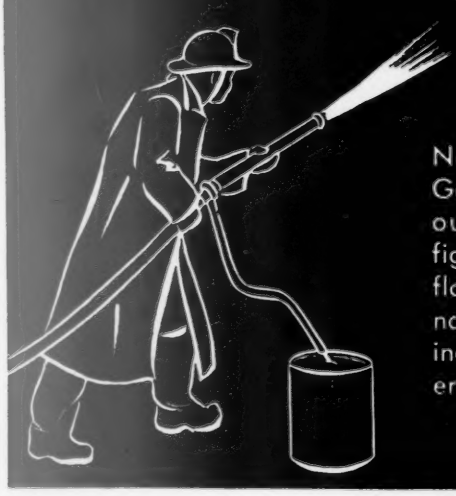

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TABLE 3. Corrosion in distilled water saturated with carbon-dioxide-air mixtures at 35 psi pressure.

Rates determined during 20-hr test period following initial 2-hr period. Velocity: 9-14 fpm

Per cent CO_2 and air in entering gas mixture	Average corrosion rate: 80 per cent CO_2—20 per cent air		80 per cent CO_2—20 per cent air		70 per cent CO_2—30 per cent air		30 per cent CO_2—70 per cent air	
Temperature	135 C (275 F)		100 C (212 F)		70 C (158 F)		70 C (158 F)	
Material	mdd	ipy	mdd	ipy	mdd	ipy	mdd	ipy
Tin					4.	0.0008	Gain	
18-8 stainless steel (Type 304)					0.0		1.	0.0002
Inconel	1.	0.0002	1.	0.0002	1.	0.0002	1.	0.0002
Nickel	12.	0.002	154.	0.025	538.	0.087	7.	0.001
Monel	21.	0.003	185.	0.030	355.	0.058	45.	0.007
70-30 copper-nickel					70.	0.011	72.	0.012
55-45 copper-nickel					72.	0.012	86.	0.014
Copper	33.	0.005	41.	0.007	43.	0.007	119.	0.019
Yellow brass					87.	0.015	116.	0.020
Zinc					267.	0.054	257.	0.052
Iron	58.	0.012	627.	0.13	474.*	0.095	556.	0.11

*60 per cent CO_2—40 per cent air.

content averaged 7 per cent and nitrogen 24.1 per cent. In Plant B, four samples showed carbon dioxide to vary from 16 to 44 per cent, and nitrogen 58.2 per cent. In Plant B, seven samplings from other evaporator effects in which steam side corrosion did not occur, showed the carbon dioxide content of non-condensables to vary from 0.3 to 0.9 per cent with an average of 5 per cent, oxygen average 19.4 per cent, and nitrogen average 75.6 per cent.

Laboratory tests were made to determine what conditions of carbon dioxide-air ratio were most conductive to attack on nickel by steam condensate. As steam condensate in an operating evaporator is condensed from the gas phase and thus may become saturated with the non-condensable gases present, the laboratory tests could be made in water through which various gaseous mixtures of carbon dioxide and air were bubbled in sufficient quantity to saturate the solution under the pressure and temperature conditions selected. Movement of the condensate over the tube surface was simulated by moving the test specimens at a velocity of 8 to 14 fpm.

Tests were made in a closed autoclave at various temperatures under 35 psi gauge pressure with some additional tests at 10 psi pressure. Mixtures of carbon dioxide and air in the saturating gas were varied from 100 per cent CO_2-zero air to zero CO_2-100 per cent air in 10 per cent intervals. Both distilled water and tap water were used in tests. Table 2 gives the results of 20-hr tests in the distilled water-gas mixtures at 70 C (158 F) and 120 C (248 F).

Early in the work it was discovered that the corrosion rate of nickel was somewhat increased by the presence of dissolved iron in the steam condensate. Consequently, additional tests were made in which samples of ingot iron were present in the test solutions at the time nickel was tested. although separated galvanically from it. The results of these tests also are given in Table 2. For comparison with nickel, tests of some other metals and alloys were made under several of the most corrosive conditions. Results are shown in Table 3.

From this test work, the following conclusions were drawn:

1. Appreciable corrosion of nickel can be expected in steam condensate saturated with mixtures of carbon dioxide and air under 35 psig, where the percentage of carbon dioxide in the gas mixture is between about 95 per cent and 55 per cent. With higher or lower carbon dioxide percentages in the mixture, corrosion is negligible.

2. The presence of dissolved iron in the condensate can be expected to extend the critical range to include mixtures of non-condensables containing 40 per cent CO_2 and 60 per cent air.

3. In these critical ranges corrosion of nickel is greater in condensate at 70 C than it is at 120 C.

4. Corrosion is considerably greater under 35 psi pressure than under 10 psi pressure, due to the greater solubility of the gases at the higher pressure.

5. Corrosion rate of nickel in steam condensate frequently decreases with time and sometimes does not occur at all due apparently to build-up of a protective film. Under the most corrosive conditions, however, this film cannot be depended upon and long time rates well over 100 mdd likely are to be encountered. Such rates are high enough to account for the observed corrosion of evaporator tubes.

Any treatment of the steam that would keep the composition of non-condensable gases in the safe range of carbon-dioxide content would prevent corrosion of nickel. This could be accomplished by: Complete removal of all non-condensables; complete removal of oxygen; or removal of sufficient carbon dioxide or addition of enough air to keep the carbon dioxide concentration below 40 per cent.

In practice, the problem was solved in one plant by the installation of boiler feed water deareators and by proper venting of non-condensables from the steam section of evaporators. In another plant it was not practical to improve the steam and the problem was solved by substituting inconel for nickel. Inconel is almost as resistant to caustic as nickel and is resistant to the critical compositions of steam condensate.

● **Case 5. Effect of an inhibitor.** This case involved the unexpected corrosion of 5 per cent nickel steel tubes in a black liquor evaporator in a Kraft pulp mill. In the No. 1 exaporator body black liquor was evaporated at 245 F to a gravity of 30 Bé (at 60 F). Steam pressure was 35 psi. The evaporator was equipped with 400 tubes, each 2 in. OD by 10 gauge by 22½ ft long. These tubes were giving a life of 10 to 12 months, showing a corrosion rate several times that experienced in some other plants.

Laboratory tests were made in samples of black liquor from this plant as well as from another plant where 5 per cent nickel tubes were giving good performance. These were 20-hr tests at 240 F and 200 fpm velocity.

The liquor from this plant gave a corrosion rate of 333 mdd (0.062 ipy), whereas that from the other gave only 5 mdd (0.008 ipy). This difference in performance could not be accounted for by the customary analyses for caustic and sulphide contents. In fact the samples showing the low corrosion rate contained more sulphide than the other.

Samples of two black liquors of similar strength were obtained from another plant and corrosion rates of 5 per cent nickel steel did not exceed 6 mdd in either sample in 48-hr tests at 245 F and velocities up to 430 fpm. Glass insulators were used with specimens in these tests, which may have been the cause of low corrosion rates as discovered in later work.

With the thought that wear of tubes may have been due to abrasion by entrained solids in the black liquor, additional samples were obtained from an-

TABLE 2. Corrosion of nickel in distilled water saturated with carbon dioxide-air mixtures at 35 psi pressure.

Rates determined during 20-hr test period following initial 2-hr period. Velocity: 9-14 fpm

Percentage of carbon dioxide and air in entering gas mixture	Average corrosion rate of nickel: No iron in water—At 70 C (158 F)		No iron in water—At 120 C (248 F)		Dissolved iron present—At 70 C (158 F)		Dissolved iron present—At 120 C (248 F)	
	mdd	ipy	mdd	ipy	mdd	ipy	mdd	ipy
100 per cent CO_2— 0 per cent air	4.	0.0006	5.	0.0009	1.	0.0002	1.	0.0002
90 per cent CO_2— 10 per cent air	153.	0.025					107.	0.017
80 per cent CO_2— 20 per cent air	352.	0.057	42.	0.007	249.	0.040	85.	0.014
70 per cent CO_2— 30 per cent air	538.	0.087	19.	0.003			112.	0.018
60 per cent CO_2— 40 per cent air	138.	0.022	20.	0.003	554.	0.090	73.	0.012
50 per cent CO_2— 50 per cent air	8.	0.0013	10.	0.0016	561.	0.091	130.	0.021
40 per cent CO_2— 60 per cent air	8.	0.0013			58.	0.009	111.	0.018
30 per cent CO_2— 70 per cent air	7.	0.0011					14.	0.002
20 per cent CO_2— 80 per cent air			7.	0.001			8.	0.0013
10 per cent CO_2— 90 per cent air	1.	0.0002						
0 per cent CO_2—100 per cent air	0.0		0.0		2.	0.0003	1.	0.0002

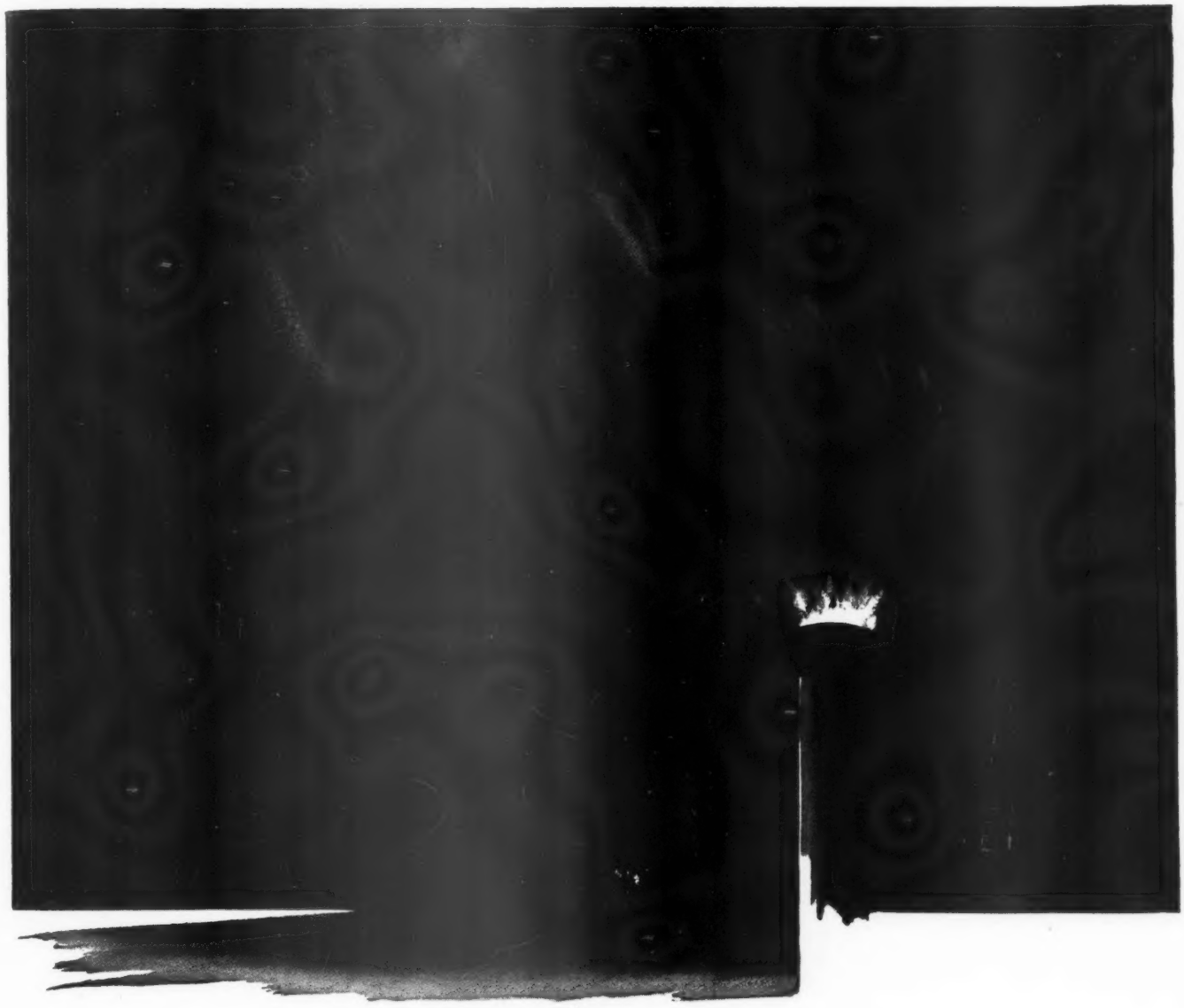

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TABLE 4. Corrosion by 45 per cent sulphuric acid with and without 1.5 gpl copper at 250 F.

Velocity of specimens: 1728 rpm (200-1000 fpm). Duration of tests: 18 hr

Material	Average corrosion rate: C.P. acid solution with no copper added		C.P. acid solution with 1.5 gpl copper added as $CuSO_4$	
	mdd	ipy	mdd	ipy
Copper	6550.	1.06	.....	....
53 Ni, 22 Mo, 22 Fe alloy	83.	0.014	5800.	0.95
60 Ni, 32 Mo, 6 Fe alloy	540.	0.084	1230.	0.19
51 Ni, 19 Mo, 17 Cr, 5 W, 6 Fe alloy	365.	0.059	2360.	0.38
85 Ni, 10 Si, 3 Cu alloy	70.	0.013	2790.	0.51
63 Ni, 30 Cu, 4 Si alloy	296.	0.048	3280.	0.54
60 Ni, 21 Cr, 6 Mo, 4 Cu, 1 W, 6 Fe alloy	635.	0.11	7850.	1.37
22 Ni, 19 Cr, 3 Mo, 1 Cu, 1 Si alloy	280.	0.052	6000.	1.10
24 Ni, 20 Cr, 3 Mo, 3.25 Si, 2 Cu alloy	725.	0.13	5850.	1.10
14.5 Si cast iron	20.	0.004	9.	0.002

other plant where solids were high. In one sample solids were filtered out and the other used as received. Corrosion rates in both samples were approximately 150 mdd in 48-hr tests at 255 F, but rates were slightly higher at a velocity of 25 fpm than at 475 fpm, indicating that abrasion by solids was not the important factor.

Koroseal insulators were used in these tests; however, in some preliminary tests, glass insulators were used. The glass parts were corroded rapidly by the hot caustic, but it was noted that corrosion rates were very low when they were used. In 96-hr tests in the unfiltered liquor containing 12 grams dissolved glass, at 255 F and 475 fpm velocity, corrosion rates did not exceed 6 mdd.

Further investigation showed that the presence of dissolved silicates can be a potent inhibitor of corrosion in Kraft black liquors, both with alloy steel and mild steel, and that variations in the normal occurrence of silicates could well account for differences in corrosion by these liquors from plant to plant.

● **Case 6. Effects of velocity and contamination by corrosion products.** In another case an oil refinery experienced unexpectedly severe corrosion of the bubble caps and plates of a copper bubble tower handling a 45 per cent sulphuric acid solution at 250 F, and also of a 60 per cent nickel, 32 per cent molybdenum, 6 per cent iron alloy pump handling the acid from this tower. Prior to installation of this equipment corrosion tests had been made which showed a corrosion rate of 0.022 ipy for copper and which appeared to them to be low enough to justify its installation. Other tests with nickel-molybdenum alloy in the pure acid solution, apparently at low velocity, had shown a corrosion rate of 0.009 ipy for this material.

The original tests had apparently failed to take into account the high velocity conditions existing through bubble caps and plate openings, and the fact that the corrosion rate of copper in sulphuric acid solutions is greatly increased by high velocity conditions. At any rate these parts failed quickly. Furthermore, solution of the copper in the acid built up the copper sulphate content of the acid to the point where it corroded the nickel-molybdenum alloy pump rapidly. Corrosion of this material is increased considerably by the presence of oxidizing salts in acid solutions, and also by high velocity conditions.

In order to demonstrate that these were the factors causing the high corrosion rates, it was necessary to make a number of laboratory corrosion tests in 45 per cent sulphuric acid at 250 F, with and without copper additions, under high velocity conditions. Analysis of the plant acid showed that it contained 1.54 grams per liter copper as copper sulphate so that amount of copper was added to the laboratory solutions. High velocity conditions were obtained by mounting the test specimens on a stirrer shaft turning at 1725 rpm so that velocities over the width of the specimens varied from 200 to 1000 fpm depending upon the distance from the center of the stirrer shaft. Duration of tests was 18 hr. A number of other alloys were also tested to determine which materials would be most likely to give satisfactory performance under the plant conditions. The results are given in Table 4. Two specimens of each material were tested and the average is shown.

Check tests with the nickel-molybdenum alloy in plant acid containing 1.54 grams per liter copper and at 1725 rpm gave an average corrosion rate of 1240 mdd.

These tests showed the accelerating effect of combined copper content and velocity and revealed that the only suitable alloy for use as a pump under the conditions would be 14.5 per cent silicon cast iron. The tests in pure acid also showed the strongly accelerating effect of velocity on the corrosion rate of copper, and to a lesser extent on the nickel-molybdenum alloy.

● **Case 7. Effect of temperature.** This case stemmed from a request for the suggestion of a better composition of cast iron to withstand corrosion encountered in 24-in. pipe lines used to carry sulphur dioxide from sulphur burners to coolers. The design of the plant was such that primary cooling of the gases was supposed to occur in these lines. The cast-iron lines suffered severe corrosion with the formation of thick layers of iron sulphate that had to be removed at intervals.

After considering the details of the installation, the conclusion was reached that the iron pipes were operating with the inner surfaces at temperatures below the dew point of the sulphuric acid formed along with the sulphur dioxide. The accumulated layers of corrosion products appeared to aggravate the condition by absorption of the condensed acid. On this basis it was recommended that, instead of substituting another material for cast iron, the next set of pipes be installed with asbestos lagging on the outside. At first there was some opposition to this on the part of the plant operators who naturally questioned the wisdom of insulating a pipe line that was supposed to act as a cooler. To overcome this objection the opinion was hazarded that the lagged pipes would be more efficient as coolers than the bare ones had been, based on the expectation that if the lagging was effective in preventing corrosion there would be no accumulation of corrosion products inside the pipes. It was felt that these corrosion products offered a greater barrier to heat flow than the lagging it was proposed to apply.

The pipes were lagged as directed and over a prolonged period there was no further corrosion and the gases in the lagged pipes were cooled more than in unlagged parallel lines operating under similar conditions. Eventually all the units were lagged and this corrosion problem was eliminated permanently and at small expense.

Additional examples could be cited involving practically all the metals and alloys. In some of these cases it would have been difficult to foresee ahead of time that the trouble would occur, based on the knowledge then available. In many of them, trouble could have been avoided by a careful consideration of the possible effects of all of the corrosion factors involved. In designing new process equipment, or in planning changes in operation of existing equipment, it would be prudent to propose and answer for one's self a number of specific questions designed to cover the possible sources of trouble. A suggested list of such questions has been provided by S. W. Shepard.[1] When unexpected corrosion does occur in spite of diligent efforts to avoid it, usually there is no substitute for a thorough corrosion testing program designed to eliminate the various possible causes until the responsible one is found. The time devoted to such test work is well spent since it adds to the fund of knowledge that can be applied to future problems. When made available, it will assist others in avoiding similar difficulties.

The authors wish to acknowledge the help provided by Dr. W. A. Wesley and his associates in the International Nickel Company, Inc., research laboratory, Bayonne, New Jersey, where all of the laboratory corrosion studies were made.

● **Nomenclature.**

mdd = mg. per sq. dm. per day
ipy = inch penetration per year

● **Literature cited.**

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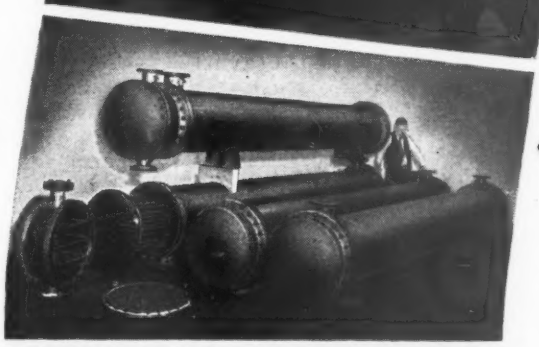

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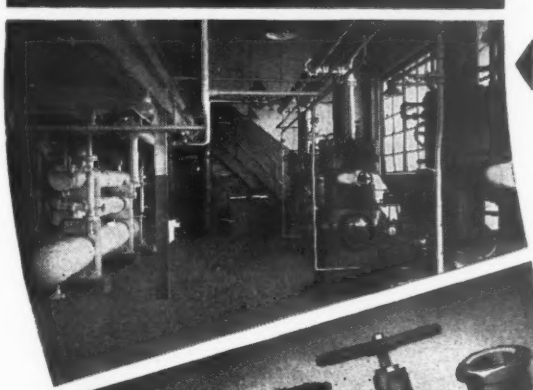

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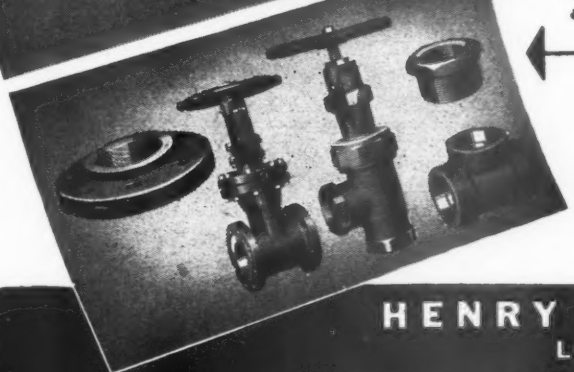

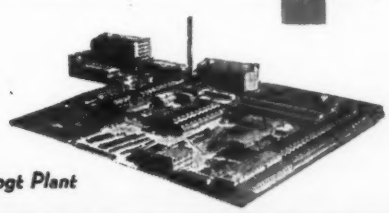

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Heat transfer coefficients for condensing hydrocarbon vapors*

By DANIEL A. DONOHUE, The Lummus Company

● **Abstract.** A simplified form of the Nusselt equation $h_m = C(L/w)^{1/3}$ is presented for calculating heat transfer coefficients for hydrocarbon vapors condensing on horizontal tubes. This simplification results from the observation that the term $0.955(k_t^3\rho_t^2g/\mu_t)^{1/3}$ in the Nusselt equation is approximately constant over the usual condensing temperature range for the hydrocarbons considered. Since solution requires that only the condensate loading w/L be known, the necessity for looking up values of the physical properties k_t, ρ_t, and μ_t at the pertinent film temperature is obviated; this results in an easy, direct, time-saving method. Application of this equation to commercial design is illustrated.

THE theoretically derived Nusselt relations[6] for calculating the heat transfer coefficient of condensation on horizontal tubes are used for designing commercial condensers. The relations are in two forms; the first is in terms of temperature difference Δt:

$$h_m = 0.725\ (k_t^3\rho_t^2g\lambda/N\mu_t\Delta tD)^{1/4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and the second is in terms of condensate loading w/L:

$$h_m = 0.955(k_t^3\rho_t^2gL/\mu_tw)^{1/3} \quad . \quad (2)$$

Where:

D = outside tube diameter, ft,

g = acceleration of gravity = 4.17×10^8 ft/hr^2,

h_m = mean value of the coefficient of heat transfer for the entire tube bundle, Btu/(hr) (sq ft) (°F),

k_t = thermal conductivity of condensate at average film temperature, Btu/(hr) (sq ft) (°F)/ft,

L = horizontal tube length, ft,

N = number of tube rows in a vertical condensing stream,

t_t = average film temp. = [(condensing vapor temp. + tube wall temp.)/2], °F,

w = rate of flow of condensate from lowest point on condensing surface, lb/hr,

Δt = temperature difference between the dew point of the condensing vapor and the outer tube wall temperature, °F,

λ = latent heat of condensation at saturation temperature, Btu/lb,

μ_t = viscosity of condensate at average film temperature, lb/(hr) (ft),

ρ_t = density of condensate at average film temperature, lb/cu ft.

Several charts[1,2,7] essaying rapid solution of the above equations have been presented. However, it should be pointed out that charts devised to solve equation (1), which require substitution of the value of temperature difference Δt, are not desirable for design use, because Δt is not readily known and must be determined by trial and error, and this necessitates more than one solution of the problem. On the other hand, equation (2) requires substitution of the value for condensate loading w/L and, since this value is known at the outset, only one solution is necessary. Therefore, equation (2) is the relation suitable for condenser design.

Constant values for the term $0.955(k_t^3\rho_t^2g/\mu_t)^{1/3}$ were observed for hydrocarbons and for petroleum fractions over the usual condensing temperature range. For this commercially important case the heat transfer coefficient may be expressed as

$$h_m = C(L/w)^{1/3} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

wherein the constant C, which equals $0.955\ (k_t^3\rho_t^2g/\mu_t)^{1/3}$, is characteristic of the compound. Equation (3) is the simplest and most facile means of solution of the condensation equation yet developed, since the only required quantity is condensate loading w/L, which is immediately available, and search to obtain the values of the physical properties k_t, ρ_t, and μ_t at the appropriate film temperature is unnecessary. The superiority of equation (3) as a ready means of calculating heat transfer coefficients for condensing hydrocarbons becomes apparent by comparison with the references listed[1,2,7].

● **Constancy of physical properties.** It was noted for pure hydrocarbons and for petroleum fractions that, as the result of the fortuitous combination of physical properties, the value of the term $0.955\ (k_t^3\rho_t^2g/\mu_t)^{1/3}$ remained constant within ±10 per cent throughout the temperature range for each individual compound.

Table 1 lists calculated values of this term for the paraffin hydrocarbons shown throughout the indicated temperature range. Viscosity values from Drickamer and Bradford[3], density values from Nelson[4], and thermal conductivity values from Smith[8] were used; since measurements of thermal conductivities are available only over the range 68 to 212 F, values at other temperatures were obtained by extrapolation.

Table 2 lists calculated values of $0.955\ (k_t^3\rho_t^2g/\mu_t)^{1/3}$ for three typical petroleum fractions throughout the indicated temperature range. Viscosity values from Nelson[5], density values from Nelson[4], and thermal conductivity values from Smith[8] were used.

● **Simplified condensation equation.** Referring to equation (3), C represents the average value of $0.955\ (k_t^3\rho_t^2g/\mu_t)^{1/3}$ for each compound listed in Tables 1 and 2. The value of C for pentane and for the 76.5 deg. API natural gasoline is 755. For these compounds equation (3) becomes

$$h_m = 775(L/w)^{1/3} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

A chart that may be used for solving this equation is given in Fig. 1; to use it, w/L must be known, or, if L is 16 ft, only w need be known. Using equation (4) or Fig. 1 as a basis, heat transfer coefficients for the other compounds can be obtained by multiplying by the following factors:

Vapor compn.	Chart multiplier
C_5	1.0
C_6	0.95
C_8	0.93
C_{10}	0.87
C_{12}	0.86
C_{14}	0.83
Light gasoline	1.0
Gasoline	0.9
Kerosine	0.88

● **Adaptation to design.** An experimental investigation of a small tube bank[9] indicates the suitability of the Nusselt relation for design use. This re-

TABLE 1—Values of C in Equation 3

tf	C_5	C_6	C_8	C_{10}	C_{12}	C_{14}
50	780	728	668	...	...	...
100	780	746	698	625	...	...
150	780	755	713	662	609	...
200	764	763	733	679	650	607
250	748	741	728	695	667	625
300	738	728	713	687	672	652
350	...	713	678	662	675	655
400	...	681	...	643	678	654
450	...	...	...	641	645	649
500	...	...	...	...	625	636

TABLE 2—Values of C in Equation 3

tf	76.5° API Natural Gasoline	57° API Gasoline	42° API Kerosine
50	727	...	...
100	762	667	...
150	785	696	621
200	806	699	664
250	...	704	676
300	...	702	684
350	...	...	675
400	...	...	665
450	...	...	652
500	...	...	628

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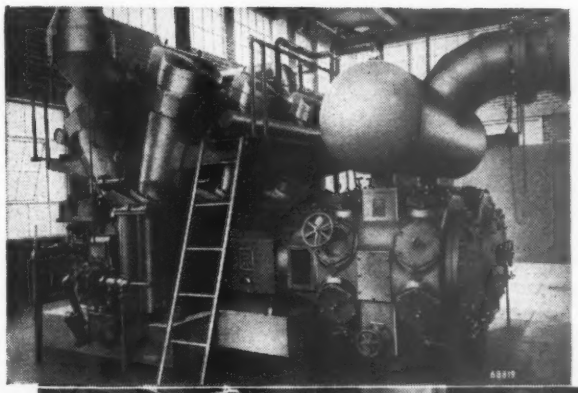

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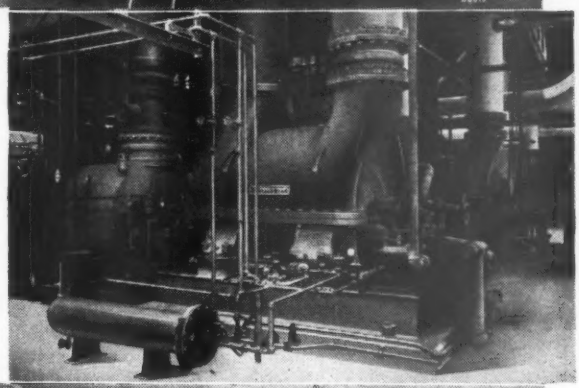

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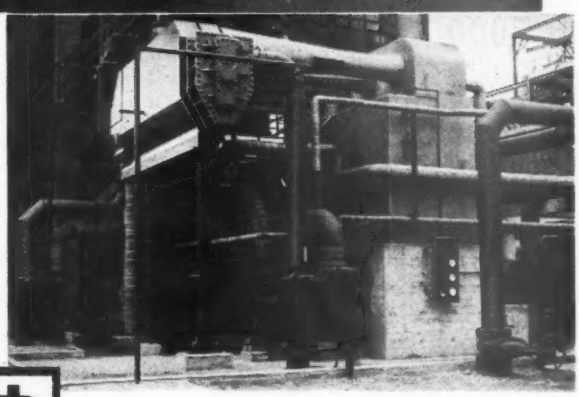

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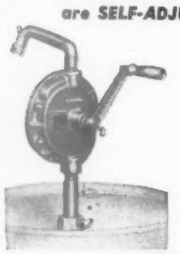

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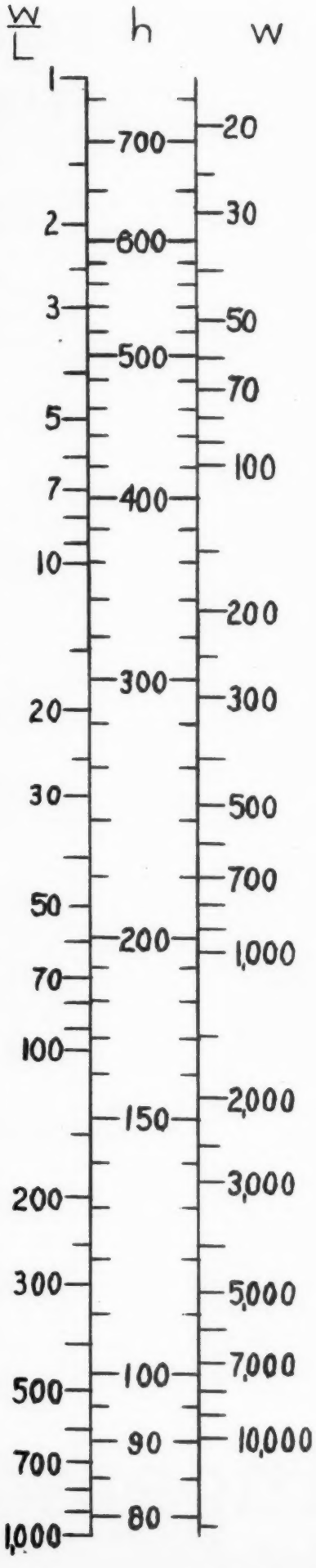

FIG. 1. Condensation of hydrocarbon vapors on horizontal tube banks. Heat transfer coefficient.

h = coefficient of heat transfer, $\frac{\text{BTU}}{\text{(hr) (sq ft) (deg F)}}$

L = tube length, feet.

w = maximum condensate flow in a vertical stream, $\frac{\text{lb}}{\text{(hr) (tube)}}$

lation is applicable only to streamline flow of condensate on the tubes, Reynolds number less than 2100; but on horizontal tubes condensate flow rarely exceeds this value. The Reynolds number for horizontal tubes is:

$$N_{Re} = D_e G/\mu_f = 2w/\mu_f L \quad . \quad . \quad (5)$$

Where:

D_e = equivalent diameter of flow area, ft,

G = mass velocity, lb/(hr) (sq ft),

N_{Re} = Reynolds number

To determine w the total flow of condensate is divided by the number of vertical condensing streams. For the case of a tube bundle having a rectangular cross-section, the number of vertical condensing streams would be equal to the number of tubes in a horizontal row if an "in line" tube spacing were used; if a staggered arrangement were used, it would be twice this number. In practice tube bundles of circular cross section are used; to resolve into a square bundle, the number of tubes at the horizontal diameter is multiplied by 0.886 when the pitch is in line and by 1.77 when staggered pitch is used.

For example, a shell-and-tube condenser was used to condense 43,000 lb per hr of pentane vapor at 140 F under an operating pressure of 15 psig. The unit used was a shell of 28-in. OD having 580 ¾-in. OD tubes on 1⅛-in. triangular pitch, 16 ft long. The number of tubes at the horizontal diameter was 27, and the average number of vertical condensing streams was $1.77 \times 27 = 48$.

$w = 43{,}000/48 = 896$ and a value of $h_m = 203$ is read from Fig. 1. The Reynolds number may be calculated from equation (5):

$N_{Re} = 2w/\mu_f L = 2 \times 896/0.436 \times 16 = 258$, which shows that the condensate was in streamline flow.

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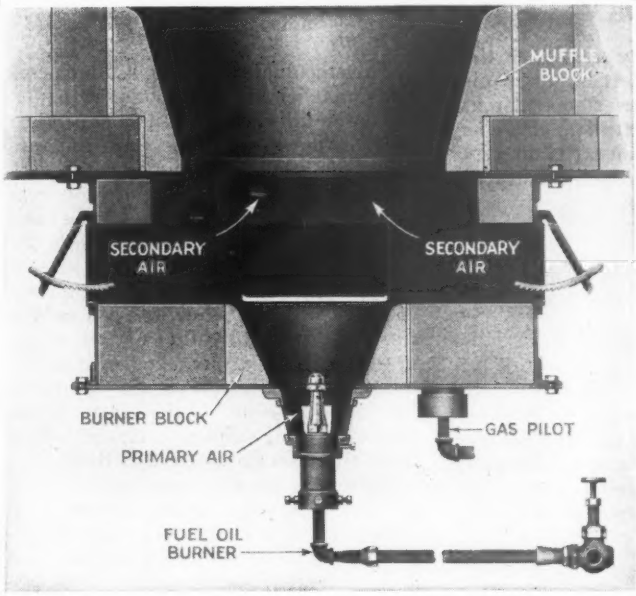

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Identification of sulphur compounds in gas mixtures*

C. S. OLDACH† and EDMUND FIELD

Ammonia Department, E. I. du Pont de Nemours and Company, Inc.

● **Abstract.** A sensitive method for identification and quantitative determination of sulphur compounds present in gas mixtures depends on differences in solubility of the sulphur compounds in an inert solvent. A complete analysis involves both an absorption and a stripping run in a multiple-plate saturator. The total sulphur content of the gas leaving the saturator is plotted against gas volume. A stepwise curve results, wherein the gas volume at which the sulphur concentration changes abruptly is characteristic of a specific sulphur compound and the magnitude of the change is a measure of the concentration of that compound. As yet an exhaustive evaluation of the method to determine its accuracy has not been made, but identification runs on partially purified manufactured gas and coke-oven gas are presented, the results of which are in general agreement with pervious industrial experience.

THE problem of completely removing sulphur compounds from gases is frequently encountered, particularly in catalytic processes. The most suitable means for effecting sulphur removal depends on the types present. Hydrogen sulphide is the most common form of sulphur encountered, but it is usually accompanied by relatively small concentrations of such organic sulphur compounds as carbonyl sulphide, carbon disulphide, and mercaptans. A new method has been developed for identifying and tetermining the concentration of these organic sulphur compounds when present in concentrations of a few parts per million. The technique is based on differences in solubility in an inert solvent used in conjunction with a highly sensitive analytical method.[1,2] It is applicable not only to sulphur compounds but to any other class of compounds for which a sufficiently sensitive analytical method is available.

The accuracy and reliability of this method of identification have not been demonstrated on gases of known composition. Because of time limitations, the plant tests were made after only qualitative evaluation of the method on known gas mixtures. However, the results obtained on partially purified manufactured gas and coke-oven gas are in sufficient agreement with previous experience in the industry[4] to justify presentation at this time.

● **Theory.** The successful method herein presented is based on the following theory:

Henry's law generally applies to the solubility of gases in inert liquid at low concentrations. This law states that at equilibrium the concentration of a gas that will dissolve in a solvent is directly proportional to the partial pressure of the gas over the solvent.

$$p = H_T x$$

Where:

p = partial pressure of solute over solution,

H_T = proportionality constant at temperature T,

x = mole fraction of solute in solvent.

In the present application the sulphur compounds studied follow closely Raoult's law, which is a special case of Henry's law in which the proportionality constant is equal to the vapor pressure of the pure solute:

$$p = p_T x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Where:

p_T = vapor pressure of pure solute at temperature T.

Since the partial pressure of a component in a gas mixture is equal to the product of its mole fraction and the total pressure,

$$p = Py \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Where:

P = total pressure

y = mole fraction of solute in gas phase.

Combining equations (1) and (2) at equilibrium one mole of solvent will contain:

$$x = \frac{Py}{p_T} \text{moles of solute} \quad . \quad . \quad . \quad . \quad (3)$$

Let n equal the number of moles of gas of composition, y, containing this number $\frac{Py}{p_T}$ of moles of solute.

Then:

$$ny = \frac{Py}{p_T} \text{moles of solute in } n \text{ moles of gas} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

or

$$n = \frac{P}{p_T} \text{moles of gas} \quad . \quad . \quad . \quad . \quad (5)$$

Thus the quantity of gas, n, which contains as much solute as one mole of liquid in equilibrium with it is dependent only on the ratio of the total pressure to the solubility coefficient or in this case the vapor pressure of the pure solute at the temperature in question. On the basis of a material balance, n is therefore the minimum quantity of the gas sample which could be used to saturate one mole of liquid with the solute and is a unique function of the solubility of this solute in the liquid. Hence an experimental determination of n reveals the solubility (or vapor pressure) of the solute. In the case of organic sulphur compounds this is usually sufficient to identify them. The relationships are the same, regardless of whether a liquid is being saturated by absorption of a component from a gas, or a gas in being saturated by stripping a component from a liquid.

To determine these minimum gas quantities experimentally, it is necessary to have an efficient apparatus for contacting the liquid and gas, so that when absorbing the sulphur from a gas at least 80 to 90 per cent of the liquid in the saturator can be saturated with the sulphur compound at the inlet gas composition before any of the compound appears in the exit gas, or when stripping sulphur from a liquid 80 to 90 per cent of the saturated liquid will be stripped of a given sulphur compound before the sulphur concentration in the exit gas drops below the original saturation value. Such an apparatus is described below.

● **Equipment.** A highly efficient saturator was constructed from twenty 60-cm (2-ft) lengths of 2 × 7 mm capillary tubing containing a total of 200 enlargements as illustrated in Fig. 1. The sections are connected by butt joints with neoprene tubing. The scrubbing liquid, No. 30 white oil obtained from L. Sonneborn Sons, Inc., is introduced at the inlet end of the saturator (through the liquid

TABLE 1. Vapor pressure of common sulphur compounds, atmospheres.

Compound	Temperature, C							Reference
	−20	−10	0	+10	+20	+30	+40	
Hydrogen sulphide	5.39	7.53	10.2	13.6	17.7	22.6	28.3	(3)
Carbonyl sulphide	3	4.3	6	8.2	11	14	18	(3)
Methyl mercaptan	0.33	0.52	0.78	1.16	1.68	2.36	3.22	(3)
Ethyl mercaptan	0.095	0.158	0.251	0.398	0.602	0.890	1.284	(9)
Dimethyl sulphide	0.082	0.138	0.226	0.362	0.552	0.812	0.15	(5)
Carbon disulphide	0.061	0.101	0.132	0.263	0.392	0.550	0.816	(5)
Thiophene	0.008	0.016	0.029	0.050	0.082	0.13	0.20	(7)

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†Present address, E. I. duPont de Nemours & Co., Inc., Belle, West Virginia.

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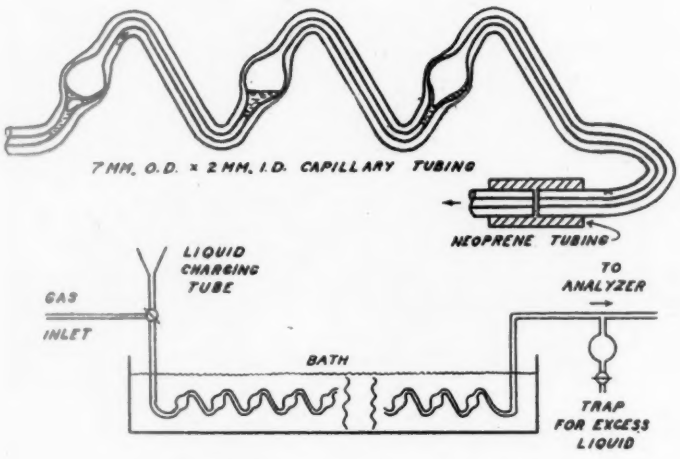

FIG. 1. Diagram of saturator.

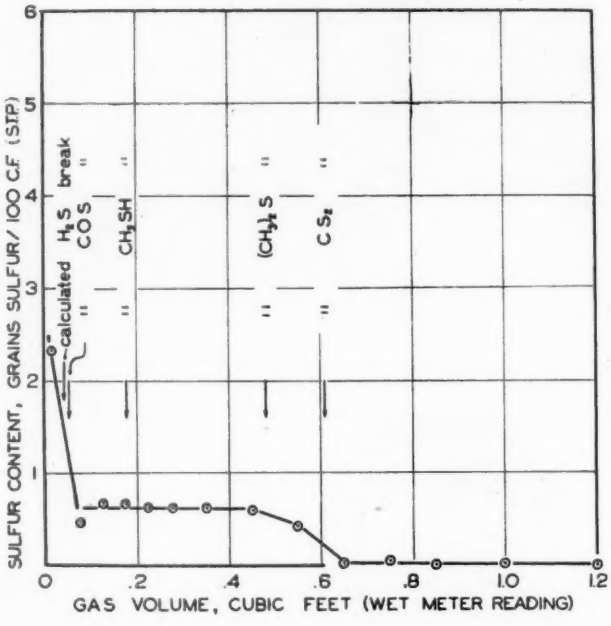

FIG. 3. Composition of blow-run gas, stripping run.

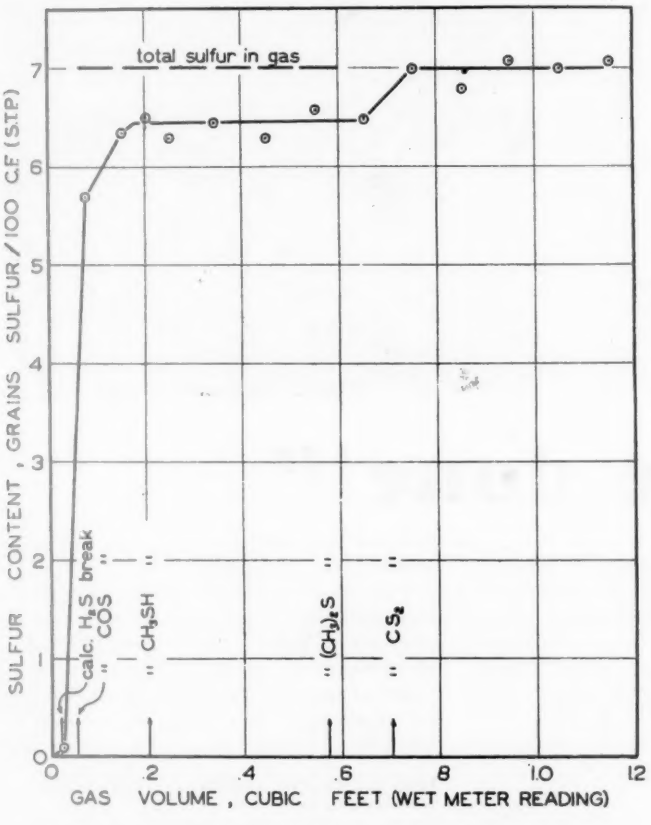

FIG. 2. Composition of blow-run gas, absorption run.

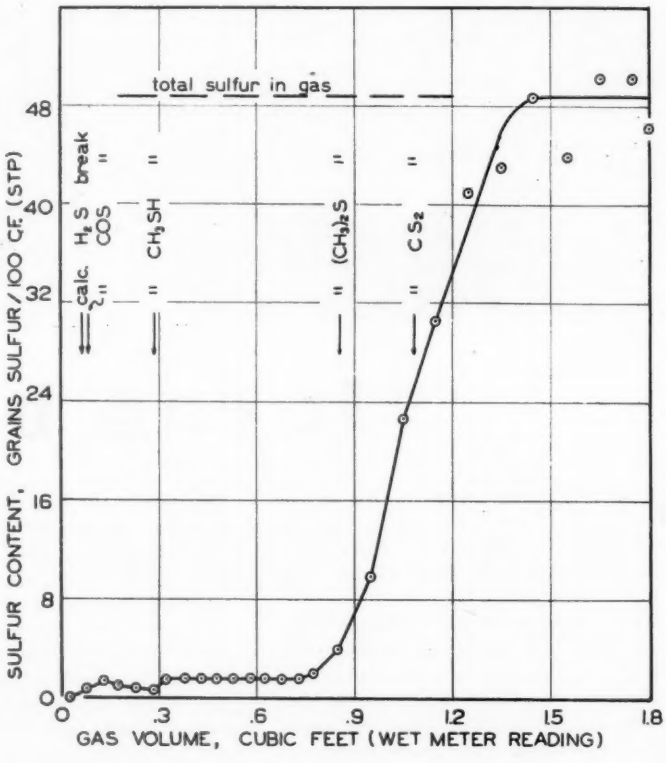

FIG. 4. Composition of coke-oven gas after preliminary scrubbing, absorption run.

charging tube) and distributed by passing a stream of hydrogen through the saturator. A very small quantity of liquid is retained in each enlargement, thereby providing 200 static pools of solvent. The entire unit is immersed in a liquid bath thermostated to ±0.5 C. A trap is provided at the exit end to catch any excess liquid carried out of the saturator.

The exit gases were analyzed by converting the sulphur compounds to hydrogen sulphide over alumina at 900 C followed by spectrophotometric determination.[1,2]

● **Sample procedure and calculation for an absorption run.** The saturator was charged with 48 ml of sulphur-free No. 30 white oil. The oil was distributed through the cells by means of cylinder hydrogen and the temperature adjusted to 14 C. Blow run gas from the generators was sampled after hydrogen sulphide removal in a Thylox unit by filling a stainless steel cylinder under pressure, and the analysis was started immediately. The gas was passed through the saturator at a rate of 0.005 cfm and led

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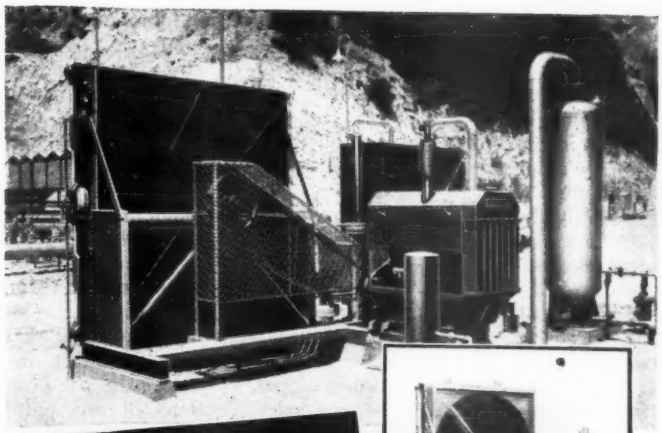

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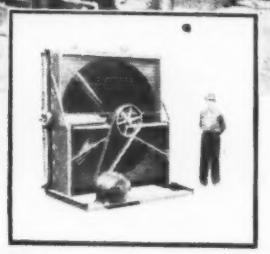

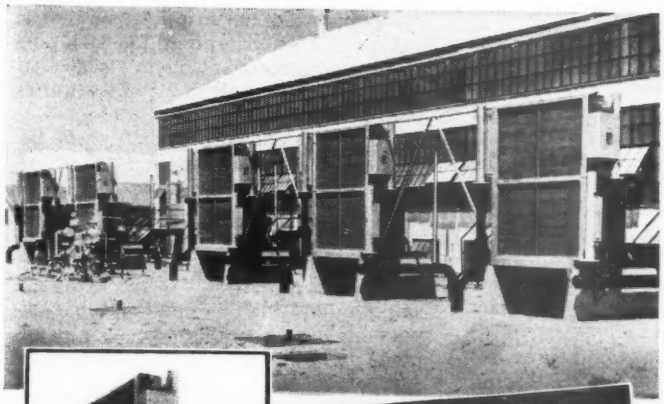

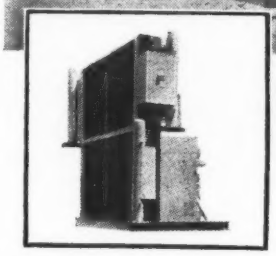

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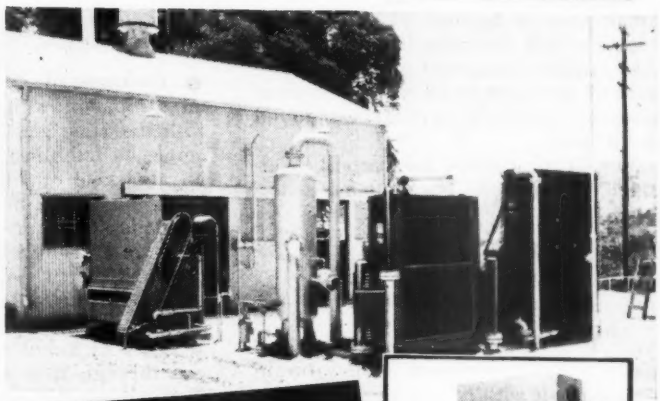

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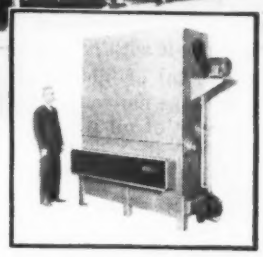

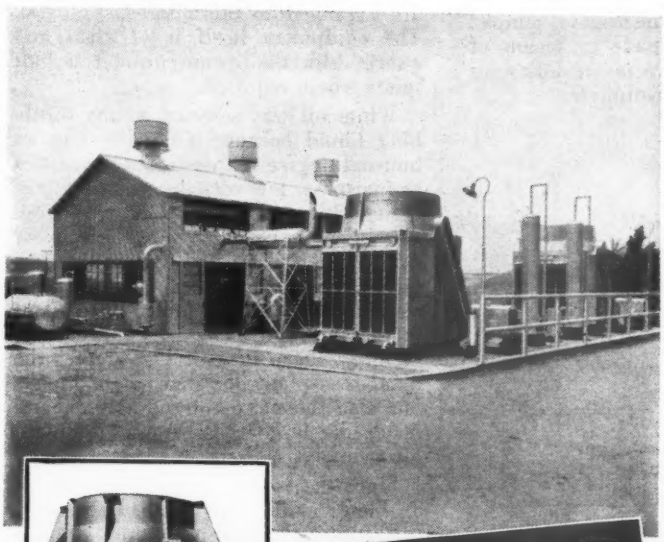

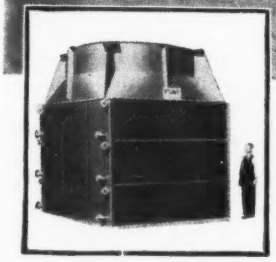

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directly to the analyzer previously described[2]; total sulphur content was determined at frequent intervals. The volume of treated gas was plotted against its sulphur content (Fig. 2). The total sulphur content of the unscrubbed gas was also determined and is shown by the dotted line.

Identification of the sulphur compounds present depends on the volume of gas corresponding to each "break" in the curve. For convenience in calculating the break volume, the vapor pressures of several common organic sulphur compounds have been collected in Table 1. These values have been interpolated, extrapolated, or calculated where necessary to put the data in the form presented. The calculated break volumes for possible sulphur compounds are indicated by the arrows on Fig. 2. When an increase in the sulphur content of the gas leaving the saturator occurs at a volume corresponding to the calculated break volume for one of the sulphur compounds it indicates the presence of that sulphur compound and the magnitude of the increase in sulphur content gives the concentration of that compound in the gas.

The break volume for carbon disulphide, for example, is calculated as follows:

$$n = \frac{P}{p_T} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$p_T = 0.308$ atm for CS_2 at 14 C.

$P = 1$ atm.

giving n = 3.25 moles of gas to saturate 1 mole of oil with carbon disulphide.

But 48 ml of oil were used (density 0.77, average molecular weight 154); so the amount of oil was

$$\frac{48 \times 0.77}{154 \times 454} = 0.000529$$

pound mole. The amount of gas required to saturate the oil in the absorber is therefore $3.25 \times 0.00529 = 0.00172$ pound mole of gas. Under the wet meter conditions this gives a calculated break volume of

$$0.00172 \times 359 \times \frac{295}{273} \times \frac{760}{741} + 0.02 \text{ cu ft}$$

of free space in absorber = 0.70 cu ft. The presence of carbon disulphide in the gas shown in Fig. 2 by the sudden rise in total sulphur at approximately the predicted 0.70 cu ft break point. The amount of carbon disulphide is represented by the increase in sulphur corresponding to the break, or 0.6 grain of sulphur per 100 cu ft (1 grain per 100 cu ft = 22.9 micrograms per liter) at standard temperature and pressure.

The similarity in vapor pressure of hydrogen sulphide and carbonyl sulphide makes it difficult to distinguish between their break points. Hydrogen sulphide was therefore determined independently (1 grain of sulphide per 100 cu ft) by absorption in cadmium acetate, made acid with acetic acid, followed by iodometric titration.[8] Since the analysis of the gas at the end of the absorption run was 7 ± 0.3 grains of sulphur per 100 cu ft, it was not possible to detect the presence of small concentrations of any sulphur compounds less volatile than carbon disulphide. However, by making a stripping run it was possible to determine the presence of any less volatile sulphur compounds because as the sulphur concentration in the gas drops below 1 grain per 100 cu ft, the precision of the analysis becomes better than ±0.1 grain per 100 cu ft as illustrated below.

● **Example of stripping run.** A 100-ml sample of white oil was saturated with the same gas in the preceding example by bubbling the gas through the oil at a rate of 70 cu ft per hr for 2 hr at —5 C in a flask fitted with a sintered-glass sparger. About 50 ml of this oil were transferred into the saturator and distributed by means of a slow stream of hydrogen, avoiding all contact with air. The saturated oil was stripped at 19.4 C by bubbling a stream of hydrogen through it at a rate of 0.007 cfm. The exit gas was analyzed for total sulphur and the sulphur content plotted against gas volume as before.

The break points for the different sulphur compounds were calculated exactly as in the preceding example. Because of the difference in temperature for the saturation and stripping, the concentration of sulphur in the absorber of gas did not correspond to that in the original sample. The correction was made by means of Raoult's law, as shown in the following example for carbon disulphide.

$$Py = xp_T \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

In this case,

$P = 1$

$p_T = 0.416$ atm at 19.4 C.

$p_T = 0.135$ atom at —5 C.

giving

$$y_{19.4}^{\circ} = 0.416\,x$$

and

$$y_{-5}^{\circ} = 0.135\,x$$

Since x, the concentration of gas in the solvent, is not changed when the saturated oil is warmed before stripping, it can be eliminated from the two equations to give:

$$y_{-5}^{\circ} = 0.33\,y_{19.4}^{\circ}$$

Consequently, the concentration of carbon disulphide found in the stripping hydrogen must be multiplied by 0.33 to give the corresponding concentration in the original gas. A similar correction was made for each component present.

The volume of gas is shown plotted against sulphur content in Fig. 3. For convenience in comparing with the absorption run on the same gas (Fig. 2), the sulphur concentrations were corrected for temperature before plotting. As may be seen from the curve, most of the hydrogen sulphide and carbonyl sulphide was stripped from the oil before good total sulphur analyses were obtained. It is for the less volatile sulphur compounds that the stripping run is most accurate. The absorption and stripping runs therefore supplement each other and a complete analysis usually requires both determinations.

Fig. 4 is included to illustrate the behavior of a gas more concentrated in sulphur. In this case the gas is coke-oven gas partially purified by scrubbing with water, light oil, and ammonium carbonate solution. This preliminary treatment removed essentially all of the hydrogen sulphide and high-boiling sulphur compounds, leaving primarily carbon disulphide and a little carbonyl sulphide.

● **Technique and sources of error.** Certain organic sulphur compounds have been demonstrated[2] to be relatively unstable even in an inert solvent such as white oil. Exposure to oxygen or to metal walls can also affect the sulphur content of a gas or solution. For this reason analyses are completed as rapidly as possible and the procedures for sampling are arranged to minimize such losses. The equipment itself is of glass and quartz with neoprene-connected butt joints where required.

White oil was selected as the scrubbing liquid because it combines to an unusual degree the desirable properties of inertness, low volatility, and low viscosity. Other solvents can be used, provided they do not react with the sulphur compounds and are not volatilized to any large extent during the analysis. A more viscous solvent might require more plates in the saturator in order to give satisfactorily sharp breaks. The greater the number of plates the sharper the breaks but also the more solvent holdup, and hence the larger gas samples required for an analysis.

Since the volume of gas required for an identification run is directly proportional to the solubility of the sulphur compounds and the volume of solvent used, it is possible to separate the break points of two sulphur compounds of similar solubilities by increasing the quantity of solvent or lowering the temperature of the solvent to increase the solubility of the sulphur compounds.

TABLE 2. Determination of sulphur content of gases.

Gas analyzed	Grains of sulphur per 100 cu ft (S.T.P.)					
	H_2S	COS	CH_3SH	CS_2	Higher boiling	Total
Coke-oven gas after removal of benzene, NH_3, H_2S, CO_2	0	0.7	0.8	46.5	0.5	48.5
Water gas from coke*						
Blue gas	0.5	3.6	0.25	0.35	0.02	4.7
Blow run gas	1.0	5.5	0	0.6	0.02	7.1

*After partial H_2S removal.

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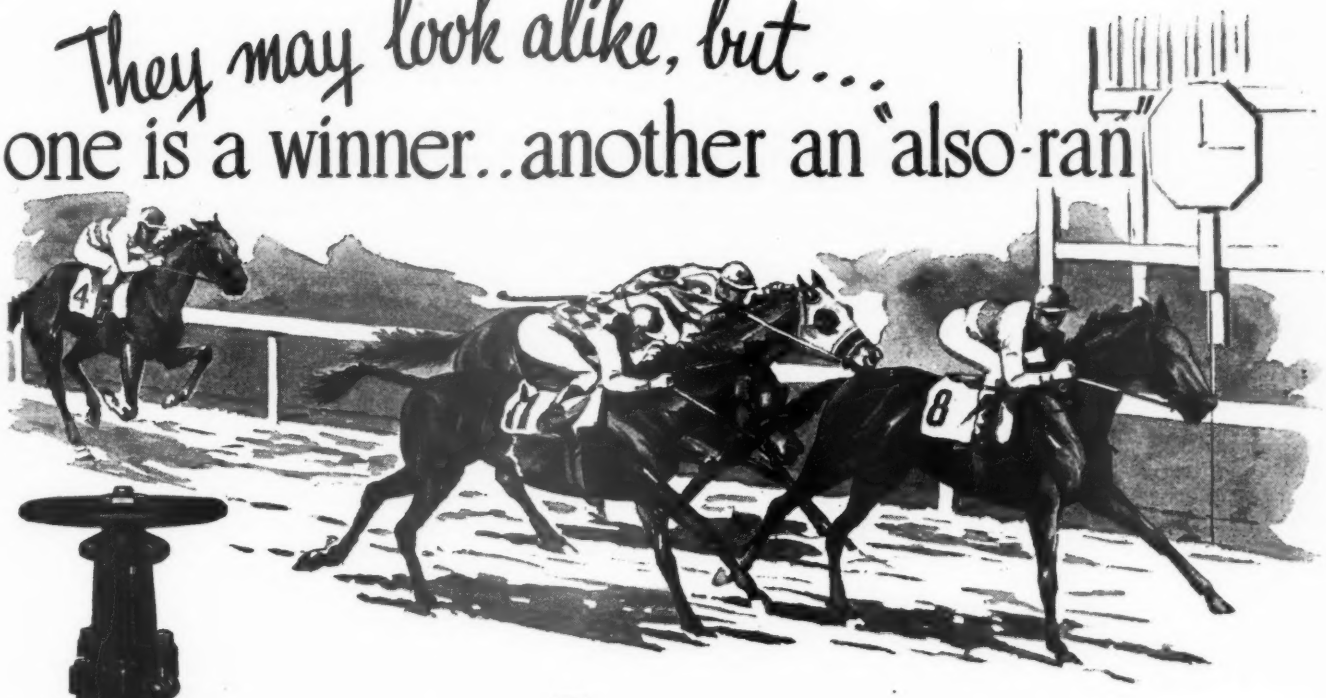

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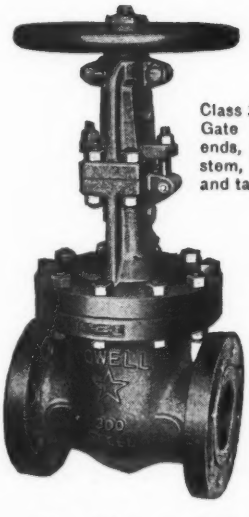

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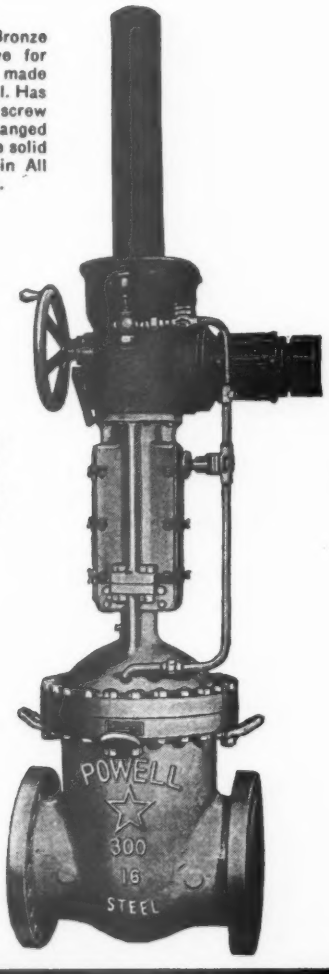

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The absorption of appreciable quantities of any component of the gas being analyzed will complicate the determination, since the net effect is to change the quantity and quality of the solvent medium. Analysis for the sulphur compounds present in a "wet" natural gas would offer this type of difficulty, since it might contain about 100 grains of gasoline per cu ft of gas. Corrections for this type of interference can be made by measuring the increase in solvent volume and determining the solubility of the sulphur compounds in the resultant solvent.

Usually both an absorption and a stripping run are required for a complete analysis of a gas. If desired, the stripping run can be performed directly on the oil saturated in the absorption run. However, the length of time required for complete saturation may lead to errors arising from instability of the solution. The saturating technique described using a simple scrubbing bottle has the dual advantage of rapid saturation and convenient use of a low absorption temperature. Low-temperature saturation followed by higher temperature stripping increases the sulphur concentration in the stripping gas and therefore the accuracy of the determination.

The organic sulphur is converted to hydrogen sulphide for analysis as previously described,[2] except that only 1 ml instead of 6 ml of alumina catalyst is employed. The smaller quantity of catalyst minimizes the adsorption of sulphur and hence gives a quicker response to changes in composition. The hydrogen sulphide may be determined by any sufficiently sensitive procedure, such as the spectrophotometric method[1] or the lead acetate–impregnated tape technique of Moses and Jilk.[6] The sensitivity of the analyses for hydrogen sulphide is of paramount importance since, as can be seen from Figs. 2, 3, and 4, it is necessary to obtain gas analyses at frequent intervals in order to detect sharp break points.

● **Results.** The results obtained with this method on three common commercial gases are summarized in Table 2.

In coke-oven gas the major impurity remaining after the usual procedures for by-product recovery is carbon disulphide, although significant amounts of carbonyl sulphide, methyl mercaptan, and high-boiling sulphur compounds are also present. In water gas, on the other hand, carbonyl sulphide is the major impurity. Similar analyses following attempted purification are especially useful in revealing which types of compounds escape treatment.

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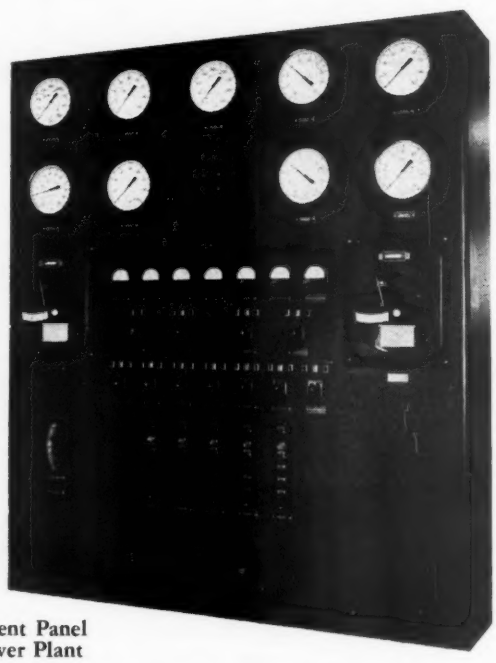

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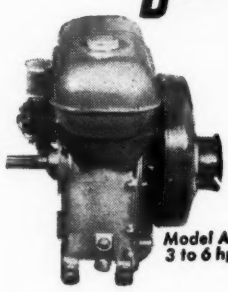

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Precision Semimicromethod for gas analysis*

By LEONARD K. NASH, Mallinckrodt Chemical Laboratories, Harvard University

● **Abstract.** An apparatus is described that is capable of complete analysis of small samples of carbon dioxide, carbon monoxide, methane, hydrogen, nitrogen, and/or oxygen. The operations of analysis are simple and reliable, and the danger of loss of a valuable sample is reduced to a minimum. With a sample of volume approximating 1 cc at N.T.P. an accuracy of a few tenths of a per cent of the total gas sample may be anticipated; but an accuracy of about 1 per cent is maintained with samples as small as 0.1 cc N.T.P. The conditions for a satisfactory fractional combustion on a platinum catalyst of hydrogen and carbon monoxide in the presence of methane and excess oxygen are defined.

IN THE course of an investigation of the gases in meteorites a sensitive method for the analysis of low-pressure gases has been developed, which provides data of high accuracy with very small gas samples, and in which the danger of accidental loss of the sample is reduced to a minimum.

Fig. 1 illustrates the apparatus, in which all the measurements are made at diminished pressures.

Only solid adsorbents are employed, and Apiezon stopcock grease is used throughout. The 1000-cc reservoir, *A*, containing purified mercury, is linked with the 500-cc chamber of the Töpler pump, *B*. The rise and fall of the mercury in *B* is controlled through stopcock 1, whose two leads give access to an aspirator line and to the atmosphere, respectively. The buret, *C*, is made from 12-mm Pyrex tubing, and is graduated from 1 to 10 cc in steps of 1 cc. The buret bulb has an additional capacity of 10 cc, permitting the accommodation of particularly large gas samples. The barometer, *D*, is made from the same piece of tubing as *C*, and is provided with the overflow attachment, *E*[2]. The difference of the height of the mercury columns in *C* and *D*, which represents the gas pressure in *C*, may be read accurately from a graduated mirror scale set behind the tubes. A calibrated thermometer set close to *C* indicates the gas temperature.

The drying tube, *F*, contains a small amount of Anhydrone, trap *G* permits convenient separation of any condensable material in the gas sample, and tube *H* contains Ascarite, for absorption of carbon dioxide and other acid gases. The combustion catalyst tube, *J*, consists of a short section of quartz capillary tubing, connected to the rest of the line through ground quartz to Pyrex joints. The capillary contains a 5-cm length of No. 22 platinum wire, and is heated by a small closely fitting furnace with Alundum core, Nichrome winding, and asbestos lagging. The presence in each branch of the adsorption train of a small spiral spring made of 4-mm (outside diameter) Pyrex tubing (not shown in the diagram) prevents any strains from developing in the line.

Stopcock 5 gives access to a series of bulbs containing various pure gases and determinate gas mixtures, while stopcock 6 leads to the line from which the gas sample is to be collected, and thence to the evacuating pumps. For cases where a small gas sample is to be collected from a very large volume it has proved advantageous to precede stopcock 6 with a small volume and a mercury diffusion pump in that order. The diffusion pump rapidly concentrates the gas sample in the small volume, from which it may be readily conveyed to the buret by the Töpler pump.

In determining the graduations of the buret, the 10-cc mark was determined directly, by weighing the mercury delivered through a stopcock temporarily attached to the bottom of the buret before the latter was sealed in place. The other points are then most simply determined after the buret has been permanently mounted—e.g., by compressing a sample of gas to the 10-cc mark, reading the pressure, and then slowly compressing it until the new pressure, corrected for any small fluctuations in temperature, is just 10/9 the former value. The new position of the mercury meniscus in the buret now corresponds to 9 cc, and may be marked as such. The other buret graduations are located in similar fashion. Nitrogen is used as the calibration gas and, by occasionally discarding part of the gas sample, the pressures are kept below 200 mm, so that no errors due to gas imperfection can be introduced.

Calibration by this method is advantageous because the buret is calibrated after it has been permanently set in place; and is calibrated in the same way, and with the same precision, as in later use. Furthermore, it is somewhat simpler to secure markings corresponding exactly to unit numbers of cubic centimeters by this method than by any other method.

● **Operations of analysis.** The dry gas sample is collected in the buret by repeated strokes of the Töpler pump, and the mercury is run up into the buret until the gas is compressed to that mark which most nearly corresponds to a sample pressure of 150 mm. The pressure is then determined with an accuracy of 0.1 mm, the temperature is read to the nearest 0.1 C, and, since the probable accuracy of the volume calibration is 0.001 cc, it becomes possible to compute the gas volume under standard conditions with a probable accuracy of 0.1 per cent.

This calculation is predicated upon the behavior of the sample as a perfect gas, a valid assumption in this instance, since it has been shown[1] that under pressures of 150 mm even a gas as imperfect as carbon dioxide behaves relatively ideally. Furthermore, any volume change produced by mixing is of negligible magnitude. Measurement at diminished pressure, as practiced in this mode of analysis, therefore not only serves to increase the effective gas volume to a readily determinable magnitude, but also obviates any aberrations due to imperfection of the gases involved.

Consider now the operations involved in the analysis of a sample containing carbon dioxide, carbon monoxide, methane, hydrogen, oxygen, and nitrogen. After measurement of the total original volume, the sample must be circulated over the Ascarite to absorb the carbon dioxide. To perform this operation the analytical train is first thoroughly evacuated, and then shut off from the evacuating pumps. The gas is withdrawn from the buret with the Töpler pump (ordinarily two or three strokes are required to empty the buret completely), and passed into the absorption train through the left branch of the three-way stopcock, 3, the mercury rising as far as the base of stopcock 3. To complete the circulatory cycle, the bulk of the gas is collected through the right branch of stopcock 3, by turning the stopcock to the appropriate position and then lowering the mercury in the pump. To ensure perfectly complete absorption this cycle may be repeated two or three times. By circulating the gas over the absorbent in this fashion it is possible to avoid any danger of the dead gas diffusion blocking occasionally encountered in the Orsat apparatus. Finally, the residual gas sample is completely collected through the right branch of stopcock 3 with three or four strokes of the Töpler pump, and conveyed back into the buret where its temperature, pressure, and volume are again measured. Recovery of the residual sample is more than 99.9 per cent complete after four strokes of the Töpler pump. By invariably collecting the residual gas through the right branch of cock 3 any water liberated by the Ascarite (or, later, in the combustion of hydrogenous material) is absorbed by the Anhydrone, and the gas reaching the buret is always in a state of uniform dryness.

To provide a small excess of oxygen for the impending combusion analysis, a suitable quantity of this gas is drawn from its storage bulb with the Töpler pump, and added to the sample in the

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FIG. 1. Analytical train.

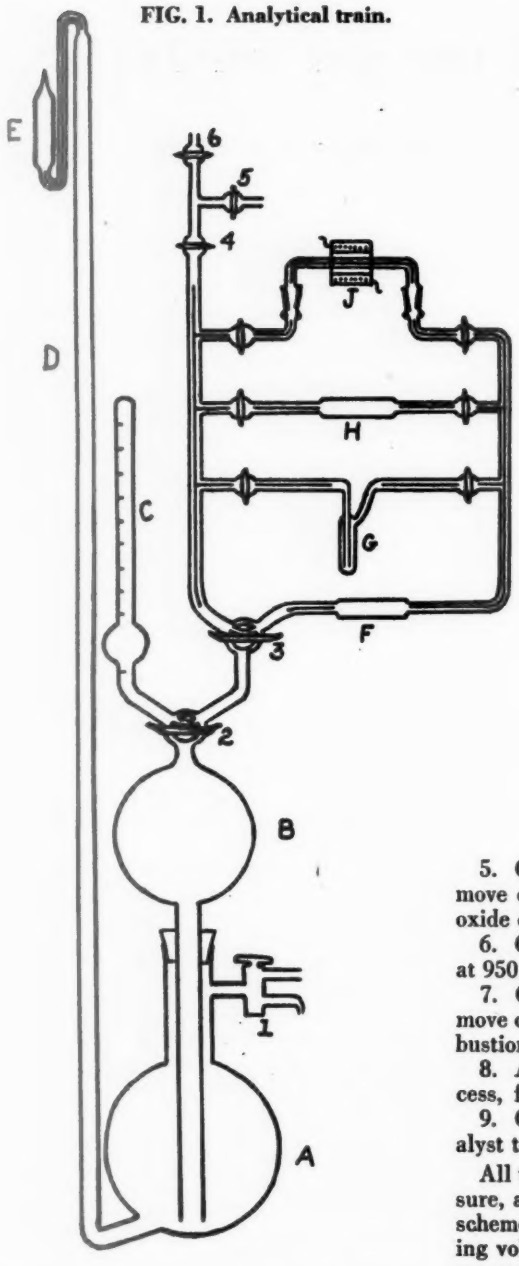
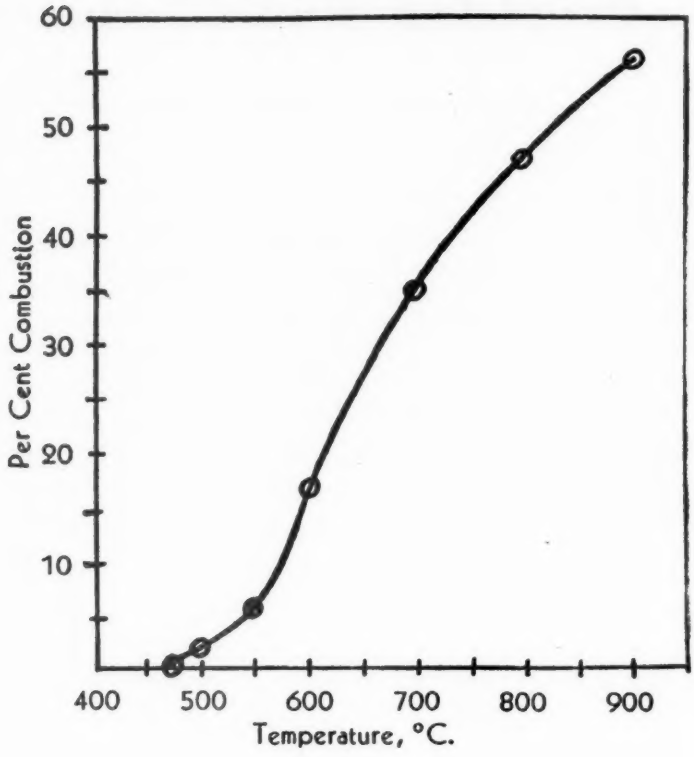


FIG. 2. Combustion of methane on platinum catalyst.



buret, whereupon the new volume is measured. The difference between this volume and that of the previous measurement represents the volume of oxygen added. The diluted gas sample is then repeatedly circulated over the combustion catalyst, which is maintained at 475 C, and the residual gas is collected and remeasured.

The further operations of the analysis are carried through by the same general procedures as indicated above, and the complete analytical scheme is shown below in outline form. The volume, pressure, and temperature are measured after each of the following operations:

1. Complete collection of original sample.
2. Circulation over Ascarite to remove carbon dioxide.
3. Addition of oxygen in small excess, for combustion.
4. Circulation over platinum catalyst at 450 C to burn hydrogen and carbon monoxide.
5. Circulation over Ascarite to remove carbon dioxide from carbon monoxide combustion.
6. Circulation over platinum catalyst at 950 C to burn methane.
7. Circulation over Ascarite to remove carbon dioxide from methane combustion.
8. Addition of hydrogen in small excess, for combustion of excess oxygen.
9. Circulation over hot platinum catalyst to burn excess oxygen.

All the readings of temperature, pressure, and volume collected in the above scheme are converted to the corresponding volumes at normal temperature and pressure. If the term v_x is made to refer to the N.T.P. volume after the x'th operation above, then the analytical results are given in the following set of formulas. It will be observed that, with the exception of oxygen, all the components are determined from relatively simple, direct formulas, and a relatively high order of accuracy may be obtained. The oxygen content is calculated indirectly and is, therefore, subject to cumulative errors; however, even in this unfavorable case, a probable accuracy of 0.5 per cent may still be obtained.

$$\frac{\%CO_2}{100} = \frac{\text{volume of } CO_2}{\text{total volume}} = \frac{v_1 - v_2}{v_1}$$

$$\frac{\%CO}{100} = \frac{\text{volume of CO}}{\text{total volume}} =$$

$$\frac{\text{volume of } CO_2 \text{ after 475 C combustion}}{\text{total volume}} = \frac{v_4 - v_5}{v_1}$$

$$\frac{\%H_2}{100} = \frac{\text{volume of } H_2}{\text{total volume}} =$$

$$\frac{2/3\ (\text{volume of contraction due to } H_2 \text{ combustion})}{\text{total volume}} =$$

$$= \frac{2/3\ (\text{total 475 C volume of contraction} - \text{contraction due to CO})}{\text{total volume}}$$

$$\frac{2/3[(v_3 - v_4) - 1/2\ (v_4 - v_5)]}{v_1} =$$

$$\frac{2v_3 - 3v_4 + v_5}{3v_1}$$

$$= \frac{CO_2 \text{ volume after 850 C combustion}}{\text{total volume}}$$

$$= \frac{v_6 - v_7}{v_1}$$

$$\frac{\%CH_4}{100} = \frac{\text{volume of } CH_4}{\text{total volume}}$$

$$= \frac{1/2\ (\text{volume of contraction due to 850 C combustion})}{\text{total volume}}$$

$$= \frac{v_5 - v_6}{2v_1}$$

$$\frac{\%N_2}{100} = \frac{\text{volume of } N_2}{\text{total volume}} =$$

$$\frac{\text{(total } N_2 \text{ and } O_2 \text{ residue after 3rd Ascarite passage—residual oxygen)}}{\text{total volume}} =$$

$$\frac{v_7 - 1/3(v_8 - v_9)}{v_1} = \frac{3v_7 - v_8 + v_9}{3v_1}$$

$$\frac{\%O_2}{100} = \frac{\text{volume of } O_2}{\text{total volume}} =$$

$$\frac{(O_2 \text{ theoretically used} - O_2 \text{ apparently used})}{\text{total volume}} =$$

$$\frac{(O_2 \text{ equivalent of } H_2, CO, \text{ and } CH_4 - O_2 \text{ apparently used})}{\text{total volume}} =$$

$$\frac{1/2\, v_{H_2} + 1/2\, v_{CO} + 2\, v_{CH_4} - (O_2 \text{ put in} - O_2 \text{ residue})}{\text{total volume}} =$$

$$\frac{\frac{2v_3 - 3v_4 + v_5}{6} + \frac{v_4 - v_5}{2} + 2(v_6 - v_7) - (v_3 - v_2) + 1/3(v_8 - v_9)}{v_1} =$$

$$\frac{3v_2 - 2v_3 - v_5 + 6v_6 - 6v_7 + v_8 - v_9}{3v_1}$$

● **Fractional combustion.** The fractional combustion on a platinum catalyst of hydrogen and carbon monoxide in the presence of methane and excess oxygen is the vital step in this procedure, for the validity of which sufficient evidence is not to be found in the literature. Although fractional combustion on oxide catalysts, especially cupric oxide, has long been known and practiced, it does not appear to be expedient if a determination of oxygen is in prospect, since these "catalysts" may themselves furnish a portion of the oxygen used in the combustion. Therefore, the possibility of using a noble metal catalyst in fractional combustion processes has been studied.

A somewhat analogous case has been investigated by Richardt[5], using a heated palladium tube. In the course of his research he noted that if hydrogen were mixed with methane, combustion of methane occurred at temperatures far too low to burn it when it was unmixed with hydrogen. This phenomenon was attributed to the strong heating of the catalyst by the combustion of the relatively large quantities of hydrogen present, and though this difficulty has been rather generally noted in fractional combustion work, it is not to be anticipated in the present instance in view of the low pressures of the gases involved.

Because of the cost, fragility, and tendency of a palladium tube catalyst to develop leaks, preliminary tests were made to discover whether an entirely enclosed platinum catalyst could be used for the fractional combustion.

In the first trial 1 gram of platinized asbestos, previously heated to redness in air, was packed into the quartz tube. It was then found that when measured small quantities of oxygen were circulated over the catalyst, while the latter was heated to bright redness, 1 to 2 per cent of the sample was lost. A second passage of the same gas sample over the catalyst resulted in a further loss of 1 to 2 per cent, so that the loss cannot be attributed to a combustible impurity in the oxygen, which, moreover, had already been treated with hot platinized asbestos during its purification. Consequently, the asbestos was discarded in favor of a small roll of platinum foil. The oxygen loss was then reduced to 0.5 per cent.

The combustion catalyst tube was then remodeled along lines originally suggested by Hempel[4], and the combustion catalyst consisted of a 5-cm length of No. 22 platinum wire inserted in the 2-mm bore of the quartz combustion capillary tube. With this catalyst renewed tests with small measured oxygen samples revealed a loss of only 0.1 per cent when the sample was circulated over the catalyst at 475 C, and a loss of 0.2 per cent when the circulation was performed at 850 C. These losses were accurately reproducible, and since they were close to the limiting experimental error, no further attempt to reduce them has been made.

The explanation of these oxygen losses, while it may lie in a trace of copper in the platinum, probably resides in physical adsorption or solution of oxygen by the platinum. Such adsorption has been reported by Sieverts[6] as increasing with rising temperature, in line with the present observations. Furthermore, the recovery of such dissolved gas would be extremely slow[7], in line with the author's experience that, after the passage of oxygen over the catalyst, prolonged evacuation is required before the combustion tube can be pumped flat.

A very small, though unmistakable, loss of oxygen (circa 0.05 per cent) when a measured sample of this gas was circulated through other parts of the line is almost certainly attributable to reaction of the oxygen with the stopcock grease, especially since a 100 per cent recovery was always secured when measured quantities of other gases were circulated through the line. The error in the case of oxygen is negligible in any event.

With the final form of catalyst tube the extent of combustion of methane-oxygen mixtures, as a function of catalyst temperature, was studied. The results shown in Fig. 2 represent the per cent combustion during a single slow passage through the catalyst tube of a uniform methane-oxygen mixture containing excess oxygen. It is apparent that at 475 C only about 0.1 per cent of the methane is burned on passage over the catalyst, yet at this temperature hydrogen-oxygen and carbon monoxide-oxygen mixtures were found to burn rapidly and completely on the catalyst. Consequently, the preliminary data collected with these binary mixtures strongly indicate the possibility of a successful low-pressure fractional combustion on a plat-

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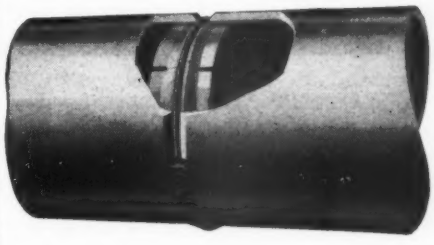

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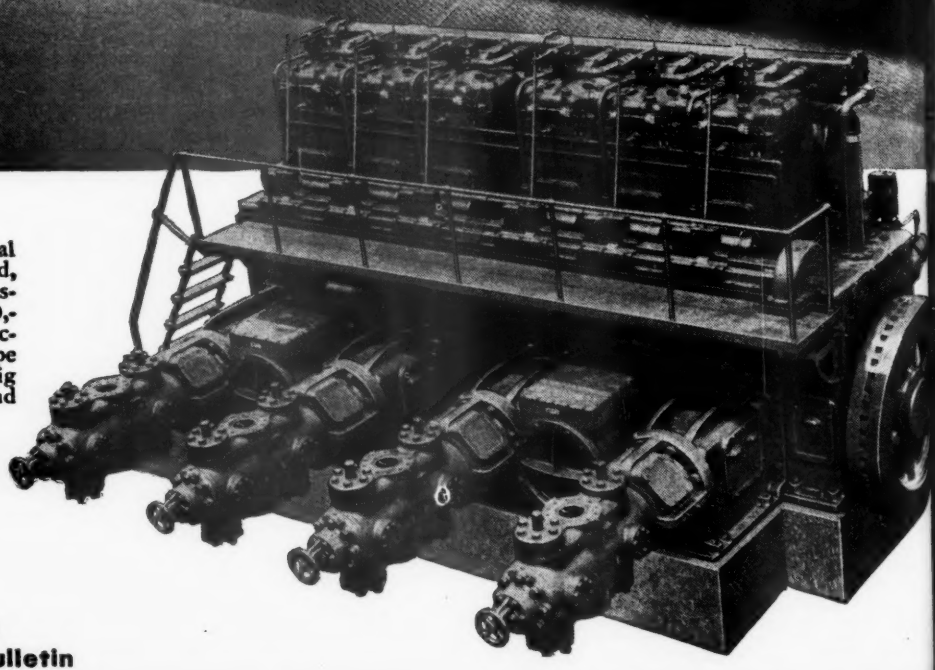
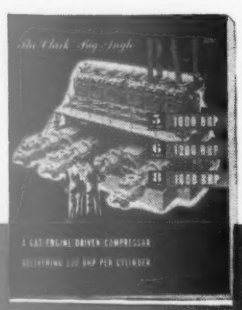


(*Above*) In Peppers Refining Co. natural gasoline extraction plant at West Edmond, Oklahoma, these three Clark BA Compressor Units, 1,000 BHP each, handle 23,500,000 cu. ft. of gas per day from 60 lbs. suction to 500 lbs. discharge into a gas pipe line. (*Right*) View of 6-cyl., 1,200 BHP "Big Angle" unit, massive but compact and accessible.



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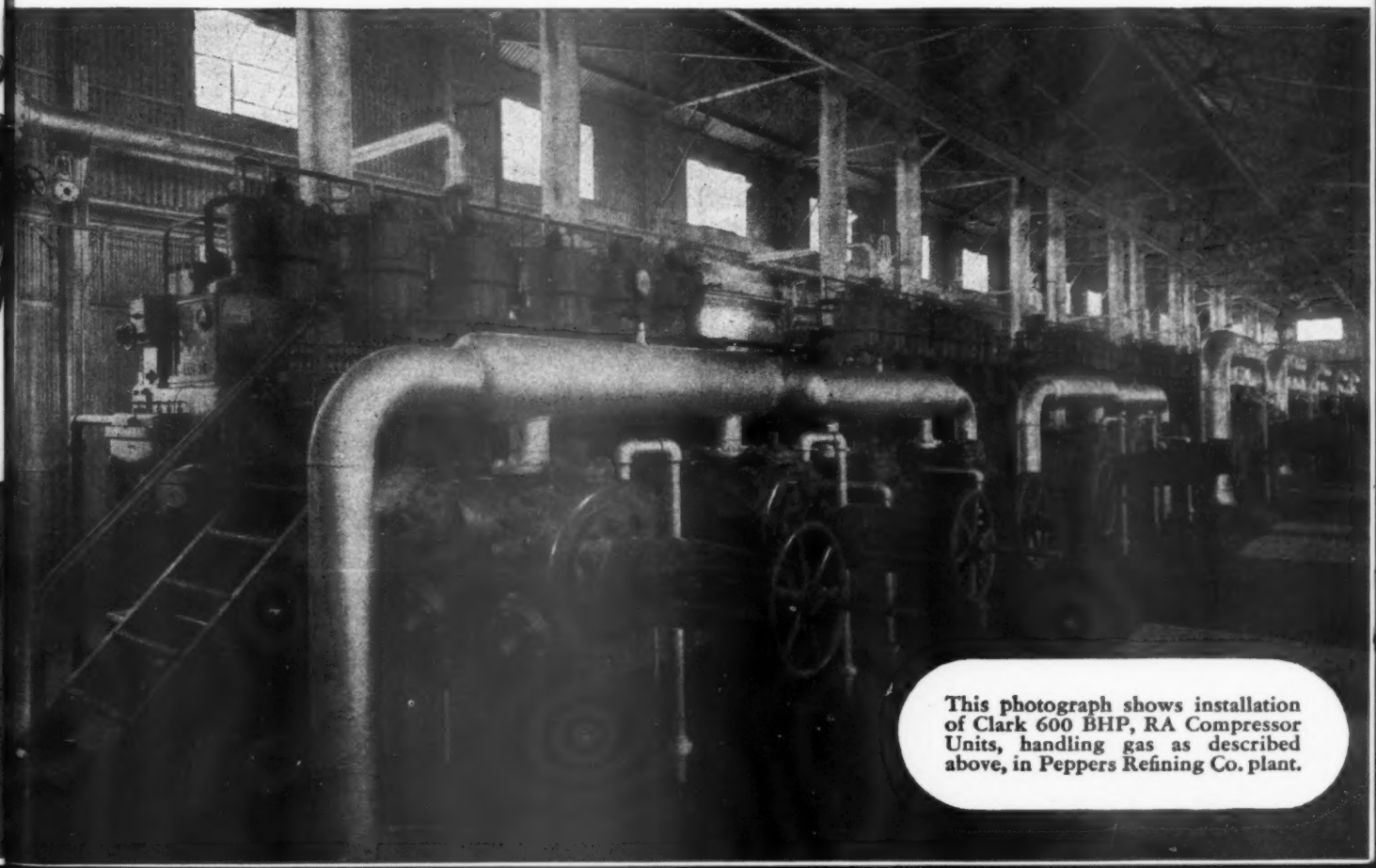

This photograph shows installation of Clark 600 BHP, RA Compressor Units, handling gas as described above, in Peppers Refining Co. plant.

inum catalyst. That such fractionation does occur satisfactorily even for mixtures of all the combustible components is proved by the outcome of control analyses.

● **Control analyses.** In preparation for the control trials, several samples of pure gases were prepared.

Hydrogen and oxygen were generated in an all-glass cell, by electrolysis of 10 per cent sulphuric acid between platinized platinum electrodes, and purified in identical trains by successive passage over fused potassium hydroxide, hot platinized asbestos, fused potassium hydroxide, and phosphorus pentoxide. The hydrogen so prepared assayed 100 per cent pure when burned with excess oxygen; and the oxygen, when freshly prepared, assayed 100 per cent pure when burned with excess hydrogen.

Despite the original high purity of the oxygen, it was found to contain small but appreciable quantities of volatile, partially oxygenated organic compounds after standing for some months in the storage bulb. The source of this material probably lies in the vaseline-rubber (Ramsay) grease originally used to lubricate the bulbs' stopcocks. Although it has been known for some time that oxygen attacks such grease[8], the formation of volatile reaction products does not appear to have been previously noted.

TABLE 1. Tests of synthetic mixtures.

Analysis No.	Total volume of sample Cc. N.T.P.		H- %	CO %	CH- %
1	1.104	Given	55.7	28.15	16.15
		Found	55.7	28.3	16.0
2	1.031	Given	58.3	31.1	10.6
		Found	58.0	31.4	10.6
3	0.926	Given	64.45	30.1	5.5
		Found	64.3	30.3	5.4
4	1.237	Given	79.3	17.3	3.5
		Found	79 1	17.5	3.45
5	1.258	Given	52.9	43.3	3.8
		Found	52.9	43.3	3.9

Considerably better though not perfect preservation was found when the Ramsay grease was replaced with Apiezon M. Analytical aberrations due to the progressive contamination of the oxygen may be avoided by always drawing the oxygen into the analytical train through a liquid air trap packed with glass wool; or by preparing a fresh supply of oxygen about once a month.

Carbon monoxide was generated by the action of hot 85 per cent phosphoric acid on 85 per cent formic acid[8]. The gas was purified by passage through a sodium hydroxide scrubber and over fused potassium hydroxide and phosphorus pentoxide. The final purity, as assayed by combustion with excess oxygen, was 99.9 per cent. The trace of impurity may have been due to slightly incomplete removal of dissolved air in the formic acid.

Methane was prepared by the cautious pyrolysis of an equivalent mixture of sodium acetate and sodium hydroxide. This crude gas was purified by successive passage through a dust trap, a dry ice trap (for the removal of water vapor), a packed dry ice trap containing a good grade of coconut charcoal previously outgassed at 500 C (for the removal of the bulk of the ethane and any other materials of low volatility), and thence into a liquid air trap. There followed ten bulb-to-bulb fractional distillations in which large fore and after fractions were discarded. The best fraction finally collected assayed 100 per cent pure on the basis of the volume contraction consequent upon combustion with excess oxygen, and also on the basis of the carbon dioxide produced in such combustion.

Several synthetic test mixtures were made up from the pure gas samples and used to test the satisfactory operation of the apparatus as a whole, and the validity of the fractional combustion in particular. The results obtained, as shown in Table 1, were gratifying in both respects.

● **Acknowledgment.** It is a pleasure to acknowledge the continued advice and assistance of Gregory P. Baxter in the conduct of this research.

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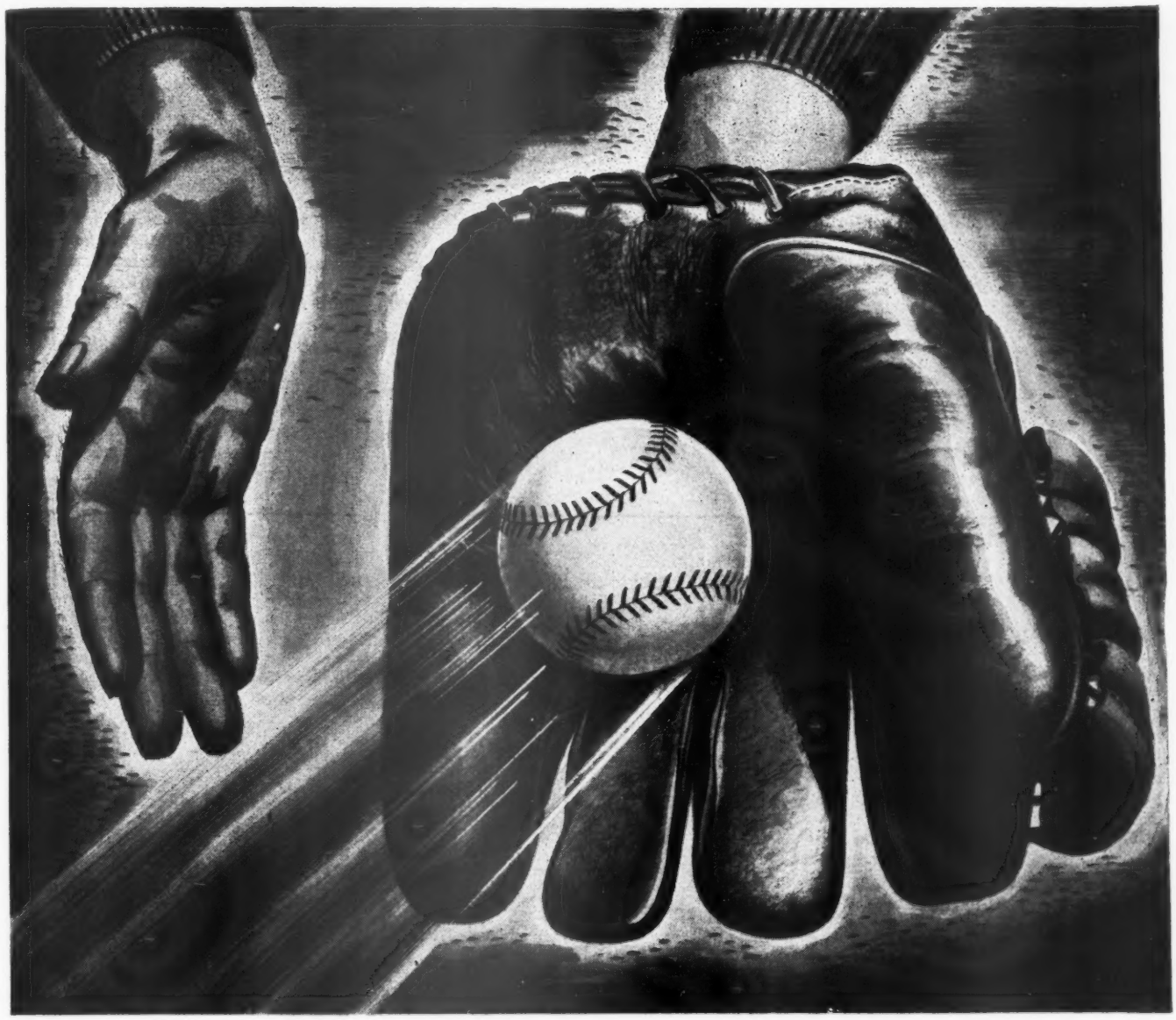

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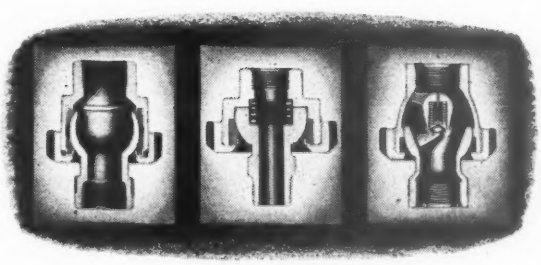

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The economic outlook for California LPG

By CLARE GARD, Union Oil Company of California, and HUGH F. COLVIN, *Consulting Engineer*

THERE are many factors that naturally present themselves in any discussion of LPG—trade term for liquefied petroleum gas and specifically propane, butane, and their mixtures. Because of the many possible variations in its production and refinery and marketing utilization, it has often been looked on as one of the problem children of the petroleum industry.

In review, propane and butane fractions are contained in field wet gas, condensate, and, to a small extent, in most light crude oils. They are also produced in large quantities in refinery cracking and reforming operations. They may be recovered partially or completely, as propane, butane, or mixtures of the two; or they may even be segregated into the various possible isomers with high degree of purity. They may be left in so-called dry gas to be sold as natural gas, used for refinery fuel, used as blending agents in gasolines, sold for domestic heating purposes, for internal-combustion engine fuel, for the manufacture of chemicals, or they may be alkylated or polymerized to yield gasoline-range components.

The economic permutations and combinations involved in such a complex pattern are extremely numerous. The following questions are typical:

What products should field absorption plants be designed to recover?

What recovery factors, what purity factors should be attained?

Is it preferable to sell propane, butane, or mixtures of the two as commercial LPG at field plants, or to transport them to refineries for gasoline blending, alkylation, or polymerization?

Should a high vapor pressure natural gasoline be produced to serve as a transportation medium for LPG fractions to the refinery, or should LPG be moved separately?

How can the greatest return be secured from LPG fractions produced in refinery operations?

Many other questions besides these could be brought to mind and much space devoted to their discussion. This paper, however, will be restricted to the following fundamentals:

1. The trend of growth of LPG demand.
2. The trend of LPG supply.
3. The future economic outlook.

● **Demand.** The rapid and continuous growth in LPG sales demand since the early 1930's is shown graphically in Fig. 1. The amazing increase has been commented on many times before, but as yet, little evidence is available to indicate a tapering off of the upward trend. It is of particular interest, however, to note that California has consistently lagged behind the total United States in rate of increase, and, if anything, this difference is being accentuated. Even with a rather conservative extrapolation of the California trend as shown on the chart, however, sales of LPG may be expected to increase about 50 per cent over present levels by the end of 1950.

Fig. 2 shows a ten-year development pattern for LPG sales by type of consumption. Throughout the period, domestic heating and internal-combustion engines provided the greatest outlet for LPG, exclusive, of course, of refinery consumption.

With regard to the future, three of the classifications warrant special comment. It is believed that considerable opportunity exists for continued expansion of domestic heating sales into marketing areas in the Pacific Northwest and the more remote sections of Northern California where LPG offers a market advantage in handling convenience over coal and wood, and where the per-therm cost differential may be lessened by increases in the costs of these competitive fuels. Increased heating demand will also be occasioned by the steady growth in population of the Pacific States.

It may be interesting at this time to compare the relative values of the various competitive fuels. Table 1 presents these relative values based on a 3.5 cents per gal value for commercial propane and 4.0 cents per gal for propane-butane mix-

FIG. 1. Annual sales of liquefied petroleum gases.
—Data from U. S. Bureau of Mines.

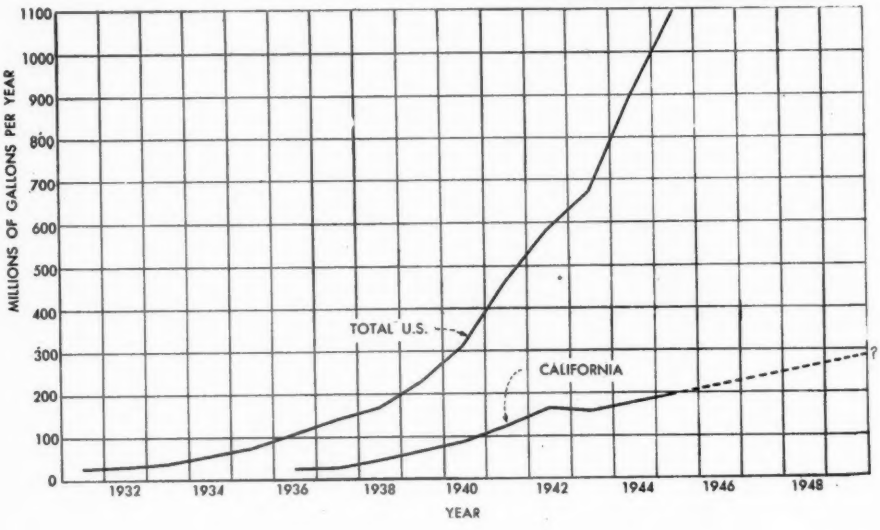
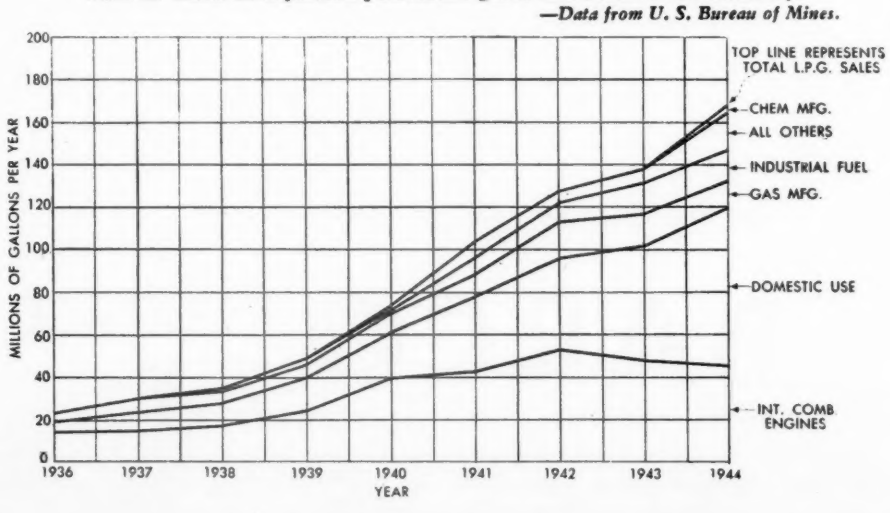


FIG. 2. Sales of liquefied petroleum gases in Pacific Coast territory.
—Data from U. S. Bureau of Mines.



*Presented before California Natural Gasoline Association, Los Angeles, October 11, 1946.

TABLE 1. Comparison of the relative values of the more common fuels* based on propane and commercial butane.

Fuel	Quantity	Relative value based on propane at 3.5c gal	Relative value based on commercial butane at 4c gal
Fuel oil (gravity 9-12)	1 bbl	$ 2.43	$ 2.62
Natural gas (1150 Btu/cu ft)	1000 cu ft	$ 0.44	$ 0.47
Coal (Anthracite-Bituminous)	1 ton	$10.54	$11.34
Stove oil (gravity 0.8314)	1 gal	5.28c	5.68c
Electricity	1 kwhr	0.13c	0.14c

*The theoretical heating values were used for the various fuels and relative values shown do not take into consideration the efficiency of conversion to useful energy.

tures. These values for propane and butane were used for discussion purposes only and other relative values may be obtained by comparison, using different basic values for propane and butane. These relative values indicate that, from a therm basis, the competitive fuel can be used to an economic advantage when its price is equal to or less than that indicated in the table.

The use of LPG in chemical manufacture may also be expected to increase, particularly from the standpoint of refinery propylenes and butylenes.

The third category in which substantial growth is still in sight is that of internal-combustion engines, both stationary and automotive.

For comparative purposes, Fig. 3 shows the distribution of LPG sales in 1944 by commodity and by use; in these charts the areas are proportional to volume of sales. Unfortunately, a complete breakdown is not yet available for 1945, nor are comparable figures available for more than a few prior years. It seems to be the consensus of the industry that the position of commercial propane will become increasingly more important because of the greater relative economic value of butane fractions for other uses. It is certain that this trend was augmented during the war by the heavy demand for isobutane for alkylation in the 100 octane gasoline program. For the next few years, however, the butane-propane mixtures known to the trade as commercial butane will probably continue to dominate the sales field. Further growth in sales of butane as such is not expected.

● **Supply.** Will the supply of LPG be able to keep up with the indicated sales demand? The answer is undoubtedly *yes* subject to certain economic qualifications that will be discussed later. Fig. 4 illustrates graphically the relationship between field plant production of LPG and sales demand. The difference between these two may be represented as net effective refinery production. This is by no means the whole story, however, and Fig. 5 (on a different scale than Fig. 4) shows how small the net refinery production is in relation to the gross production from all cracking, reforming, stabilizing, and other operations. The balancing figure representing net refinery consumption is influenced partly by the availability of physical facilities but primarily by the economic relationships between LPG sales netbacks and the equivalent value of LPG fractions for gasoline blending, polymerization, and other refinery uses. The important thing to keep in mind is that the potential LPG available from maximum refinery operations plus that available from maximum field operations far exceeds the foreseeable sales demand for the next few years. In this respect, California is quite in line with the rest of the country[1]. It must be admitted that some capital expenditures would be necessary for additional fractionating and especially storage and handling facilities before this maximum potential LPG could move into trade channels; but this also will be governed by economics; and once butane and propane fractions are produced their recovery and utilization are largely determined by practical dollar-and-cents economic analyses.

With regard to refinery production, it

[1]Oberfell and Thomas, *Oil & Gas Journal*, June 8, 1946, pp. 60-61.

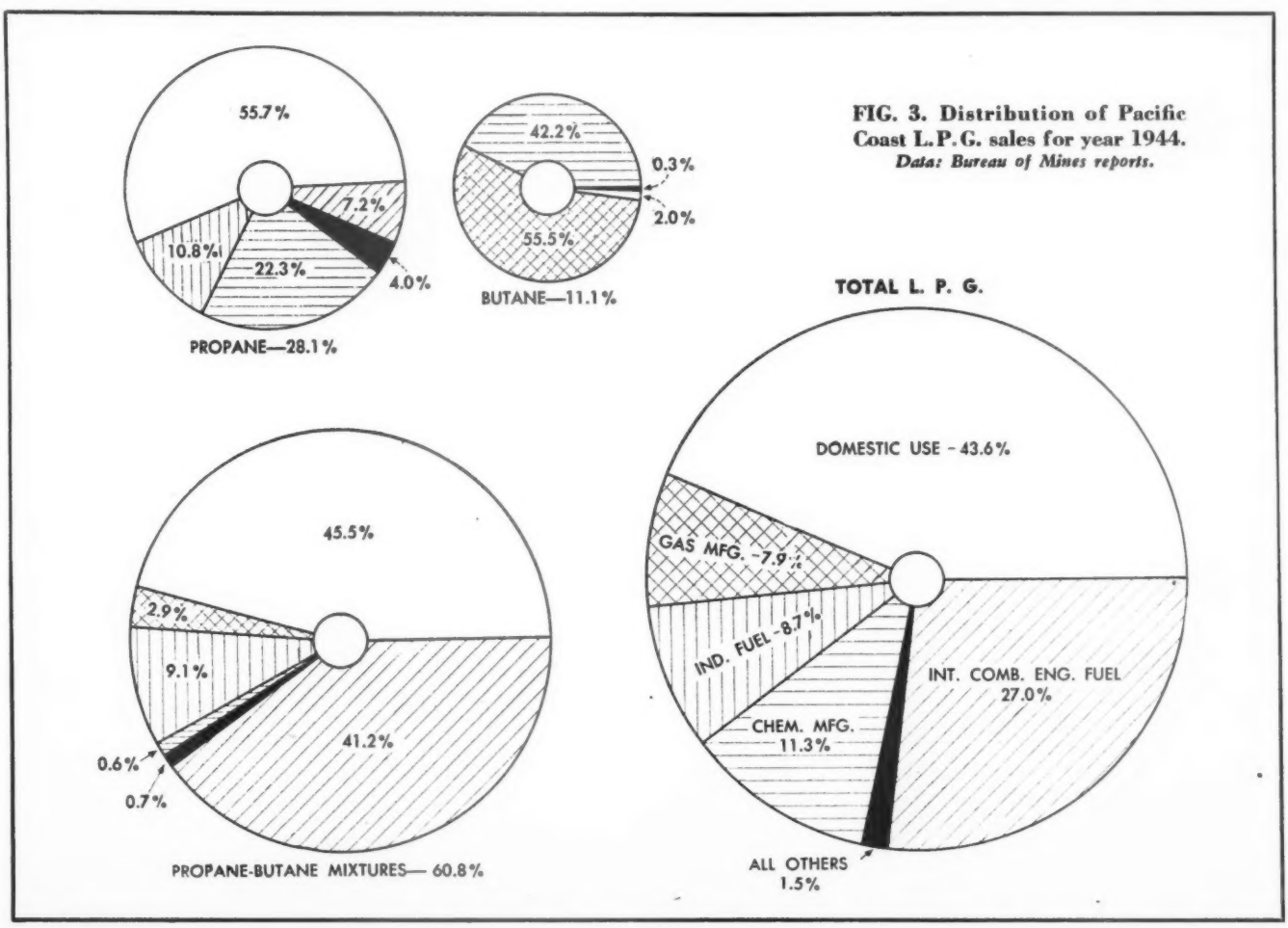


FIG. 3. Distribution of Pacific Coast L.P.G. sales for year 1944.
Data: Bureau of Mines reports.

is interesting to note the high peak in 1945 that was associated with a record volume of crude and cracking plant operations, and in particular with new catalytic cracking operations, which were one of the outstanding features of the wartime refinery expansion program. These catalytic cracking operations are continuing at a high rate and will undoubtedly be maintained permanently for reasons of gasoline quality. Aside from their effect on increasing refinery LPG fractions, these catalytic operations are noteworthy for the very large proportion of isobutane and butylenes in the effluent C_4 fraction, which has an important bearing on alkylation economics.

It is believed that the reported cracking production and refinery consumption of LPG fractions are low because the processing operations of some refineries are so closely integrated that it is not possible to measure certain LPG streams in the intermediate stages and only the net figure is reported.

An interesting hypothetical picture of the effect of cracking on refinery LPG production is shown in Table 2, where comparisons are made between straight-run distillation of crude, distillation followed by thermal cracking of gas oil and residuum, and distillation followed by recycle catalytic cracking of gas oil and thermal cracking of residuum. For better contrast, the primary products have been adjusted for a 10 lb RVP gasoline blend, using butane as a blending agent. No provision is made for alkylation or polymerization, which could be justified in most refineries and which would convert part or all of the surplus LPG to gasoline.

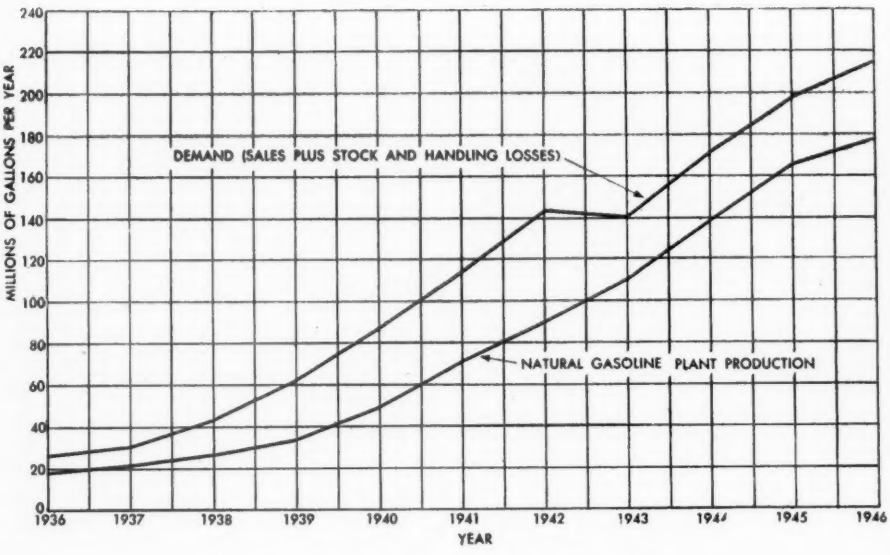


FIG. 4. Analysis of L. P. G. demand related to source of supply in Pacific Coast territory.
Data: U. S. Bureau of Mines reports.

With regard to field plant production, it seems probable that if economic conditions warrant, additional LPG can be obtained through installation of new facilities or improvement of existing ones. It is difficult to get a reliable survey of potential production from existing facilities but Tables 3 and 4 present some interesting data that were assembled recently. Some confusion apparently exists as to what constitutes "potential" production, causing unexplainable differences between actual and potential production by commodities, but it is believed the comparisons for total LPG are significant.

The indicated potential production with existing facilities in field plants is about 230,000 gal per day higher than the actual for the first half of 1946 in the case of propane, whereas the actual production of butane plus commercial butane was about equal to the indicated potential. By converting commercial butane to butane and propane on the rough assumption of a 50-50 proportion, the following comparisons are obtained for total California field LPG in gal per day:

	Actual—first half of 1946	Potentia
Propane	220,000	395,000
Butane	287,000	334,000
Total	507,000	729,000

This may be taken as rough evidence that 86 per cent of the potential butane and only 55 per cent of the potential propane are now being recovered. From Table 4 it is seen that present field plant storage facilities are sufficient to handle only 4½ days average production. This points up another problem of handling LPG, namely, the difficulty and expense of providing suitable storage to even out day-to-day surges of production or sales

TABLE 2. Effect of refinery cracking operations on LPG production. Basis 10,000 bbl per day of 30 deg Los Angeles Basin crude.

	I Straight-run distillation	II (1) Followed by thermal cracking of gas oil and residuum	III (1) Followed by recycle catalytic cracking of gas oil and thermal cracking of residuum
Product yield, bbl per day			
Propane	8	149	170
Propylene	..	327	186
Isobutane	20	101	174
Normal butane	60	222	225
Butylene	..	162	303
Total C_3+C_4	88	961	1,058
C_4Free gasoline	3,160	6,243	6,355
Gas oil	3,360	..	..
Residuum	3,390	3,109	2,642
C_2 and lighter (FOE)	304 ..	258 (617)	(317)
Total	10,000	10,000	10,000
Net products, bbl per day			
C_3	8	476	356
C_4*	(235)	(132)	149
Gasoline (10-lb. RVP)	3,475	6,860	6,908
Distillate fuel	3,360	..	..
Residual fuel	3,390	3,109	2,642
Fuel gas (FOE)	2	304	258
Loss (gain)	..	(617)	(313)
Total	10,000	10,000	10,000

Deficiency of butane in Cases I and II is net after providing for blending motor gasoline to 10-lb. RVP.

TABLE 3. Status of California liquefied petroleum gas production from field plants.

	Los Angeles Basin	San Joaquin Valley	Coastal Area	Total
1. Number of plants producing*				
Commercial propane	10	12	3	25
Commercial butane	3	9	4	16
2. Actual production first half of 1946, M gal per day†				
Propane	22	87	22	131
Butane	2	168	27	197
Commercial butane	14	146	19	179
Total	38	401	68	507
3. Potential production, M gal per day‡				
Propane	48	274	38	360
Butane	12	254	32	298
Commercial butane	5	38	28	71
Total	65	566	98	729
4. Stated capacity, M gal per day§				
Total LPG				358

*Based on individual survey—checked by CNGA data.
†CNGA data.
‡Individual plant survey based on existing facilities.
§Data from *Oil and Gas Journal* April 20, 1946, only 16 plants reported as producing LPG.

TABLE 4. Liquefied petroleum gas storage and loading facilities at California field plants.(a)

	Los Angeles Basin	San Joaquin Valley	Coastal area	Tota
Storage facilities, M gal†				
Propane	53	385	157	595
Butane	..	943	120	1,063
Commercial butane	75	420	96	591
Total	128	1,748	373	2,249
Number of plants with loading facilities.				
Truck and trailer	9	14	5	28
Tank car	1	6‡	1	8
Pipe line	1	3	..	4

*Based on individual plant survey.
†Information on storage facilities at one Los Angeles Basin plant and one San Joaquin Valley plant not available.
‡Rail facilities now being installed at two additional San Joaquin Valley plants.

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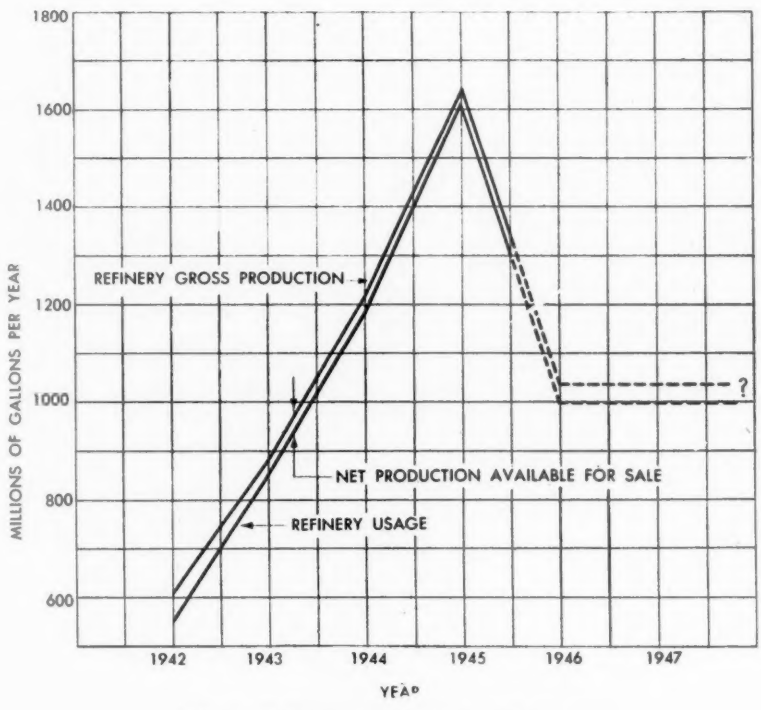


FIG. 5. Refinery production and usage of L. P. G. in Pacific Coast territory.
Data: U. S. Bureau of Mines reports.

demand in order to attain maximum annual recovery.

● **Economics.** Much pertinent information of LPG economics is of course hidden behind the secrecy of individual company operation. The following comments are to be viewed as having only general validity and must be modified by individual circumstances of transportation, refinery costs, sales netbacks, etc.

One of the most important considerations to the individual LPG producer is the disposition of his product that will bring the greatest value. At the present time, the following sequence from highest to lowest appears to prevail in California:

1. Blending agent in motor gasoline to provide front-end volatility up to limits of vapor pressure specifications. (Butane fractions only.)
2. Refinery processing of refinery LPG by catalytic polymerization, alkylation, or thermal polymerization to yield gasoline range components. (Primarily olefins and isobutane.)
3. Sales as commercial LPG.
4. Refinery processing of field LPG. (Butane only.)
5. Diversion to refinery fuel or natural gas.

Considerable question exists as to the economic value of alkylation and polymerization. Of course, the former is required for the production of high-octane aviation gasoline, but it is felt that both alkylation and catalytic polymerization can also be justified in most cases for motor gasoline production when operating on refinery LPG fractions up to the limit of isobutane or olefin availability. For field LPG, with the exception of some isobutane streams, this is probably not the case at the present time because of the effect of transportation costs, although it was necessary during the war. Thermal polymerization appears to be uneconomical in most cases even for refinery LPG. These conclusions on refinery economics are in substantial agreement with those presented in detail by Parker[2] and Perkins[3] at last year's CNGA Fall Meeting.

Construction of new plants to convert field LPG into gasoline fractions would certainly be regarded as a hazardous economic adventure at the present time; however, looking ahead over a five or ten-year period, it seems probable that because of increased gasoline demand, declining crude supply, and increased finding, producing, and refining costs, the price of gasoline will move upward. As this takes place, the equivalent value of propane and butane fractions for conversion to gasoline will likewise rise, and it is to be expected that the market price for commercial LPG will be equalized with this refinery conversion value. In this connection, Fig. 6 is of interest as a projection of the supply and demand for California crude through the year 1950. If, as is indicated, the supply of California crude falls below the demand in that period, the price levels for all petroleum products and byproducts will undoubtedly be stiffened, and LPG will be one of the beneficiaries.

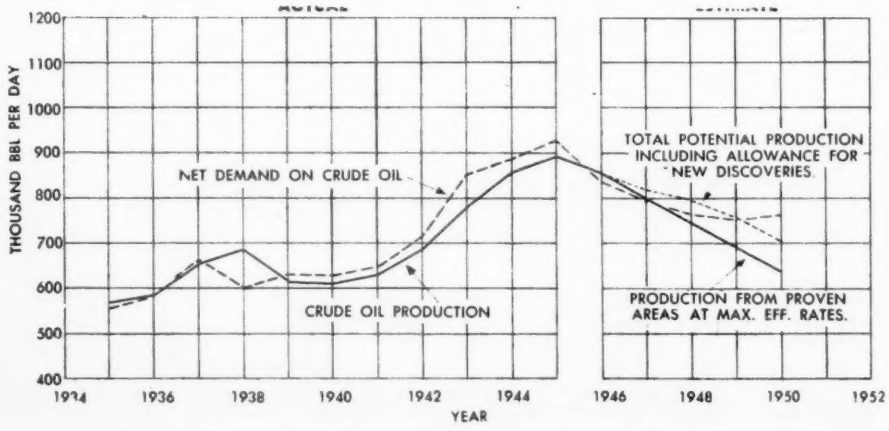
Table 5 presents production data of oil and gas for California fields for the

[2]F. D. Parker, *Proceedings 20th Annual Fall Meeting C.N.G.A.*, pp. 33-41.
[3]M. M. Perkins, *Proceedings 20th Annual Fall Meeting C.N.G.A.*, pp. 27-32.

TABLE 5. Comparison of yearly crude oil and natural gas production for California.

Year	Crude oil production, bbl per day	Natural gas production, M cu ft per day	Gas oil ratio
1935	570,000	835,253	1.47
1936	585,000	961,115	1.64
1937	655,000	918,735	1.40
1938	685,000	960,731	1.40
1939	615,000	944,964	1.54
1940	610,000	979,442	1.60
1941	630,000	985,736	1.56
1942	685,000	891,911	1.30
1943	780,000	959,910	1.23
1944	860,000	1,139,267	1.32
1945	890,000	1,245,542	1.40
1946 (est.)	855,000	1,235,738	1.44

FIG. 6. California crude oil supply and demand picture 1935-1950.
Data: U. S. Bureau of Mines reports and California Conservation Commission reports.



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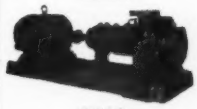

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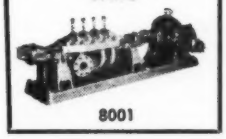

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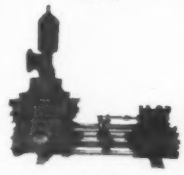

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period 1935 and 1946, inclusive. This table was prepared in the hope that it might present some relationship that would be useful in forecasting the probable LPG future. Generally speaking, the ratio of gas to crude production has not varied greatly over the years and it appears reasonable to assume that crude oil production can be used as an index to anticipated LPG production potentials.

One economic question that arises naturally in consideration of strengthening prices is that of withholding LPG from low-value uses today in order to conserve it for higher-value disposition in the future. With the current installed steel storage cost of 20 to 25 cents per gal for propane-butane mixtures and 35 to 40 cents per gal for propane, any sizeable storage plant will cost a substantial sum. Manifestly, the storage of large quantities of LPG aboveground is questionable. There remains the possibility of utilizing underground reservoirs through injection of LPG into subsurface formations. Little is known about the physical limitations of this and even less about the economic factors involved, but the problem may be worth some consideration.

One Mid-Continent producing company has reported some rather inconclusive data on underground storage that may be summarized briefly as follows:

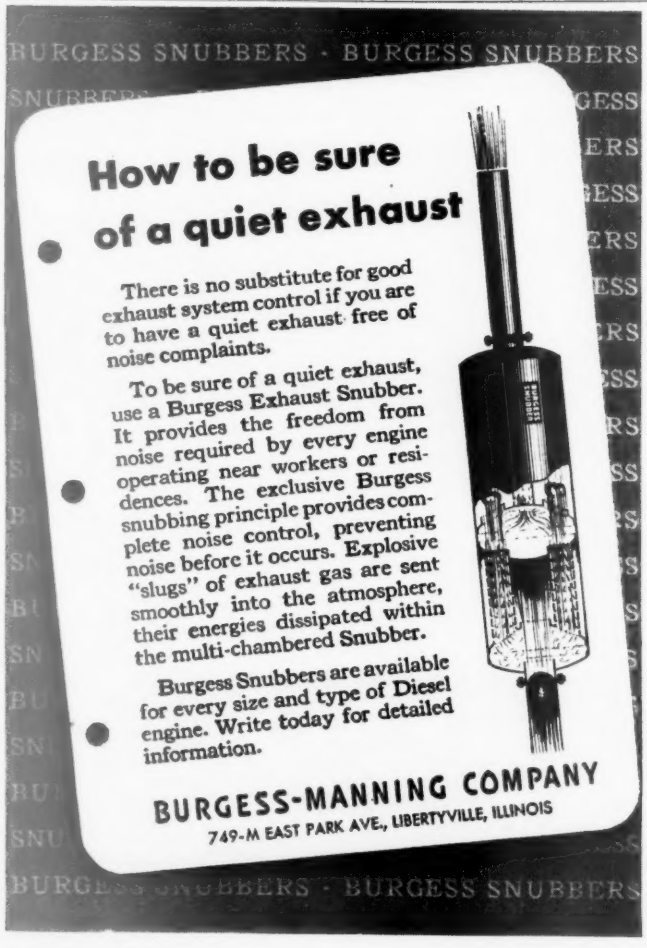
Using semi-exhausted oil reservoir strata in some cases and, in other cases, productive natural gas strata that have not been produced to any degree at all, several millions of gallons were introduced, chiefly of commercial butane with smaller amounts of propane. Good results were obtained in at least two instances where the surplus materials were introduced into the well bore as liquids and which, at least to a considerable degree, remained in the reservoirs as liquids, but little success was had in recovery of the liquids from the ground. In attempting to pump such liquids from the ground by various pumping means, the volatility was found such that at existing pressures, gasification would occur, resulting in abandonment of liquid pumping. Where reservoirs were under depleted pressures, the liquid gasified on introduction, but no particular difficulty was experienced from freezing. In one trial by another company, however, the hydrocarbons remained liquid in the ground but attempt at rapid recovery caused gasification and a tight freezing of the entire well structure necessitated prolonged discontinuance.

In one reservoir with an intermittent throughput of something like 10,000,000 gal, 90 to 95 per cent of the first injected materials were recovered in the form of vapors that were handled through the regular gas gathering and processing facilities, appearing as so much excess LPG. Complete recovery has not been attempted since. With fixed plant facilities, any additional throughput of high content propane or butane gas may overload the existing equipment to the extent that substantial increased production of propane and butane may not be fully realized. The production of such gases from storage zones to meet peak demand must be correlated properly with adequate extraction facility to give satisfactory results.

In connection with a high pressure gas reservoir, it was found when opening the well after liquid injection, that a 99 per cent pure propane could be recovered in vapor form, which, however, soon became contaminated with methane and other natural gas diluents long before recovery of any reasonable percentage of the injected liquids. Here again, the presence of other hydrocarbon diluents may affect the overall recovery of the propane and butane and proper study should be made of all factors affecting the program.

It is the tentative opinion from these experiments that where a structure small in areal extent can be found and preferably one which has been depleted of natural gas or oil at relatively shallow depths, it should be possible to introduce light hydrocarbon liquids and to recover them in large degree in liquid and gaseous form. To date, no such structure has been utilized.

The authors wish to thank George P. Bunn, of the Phillips Petroleum Company, for his comments on underground storage of LPG and W. L. Cowan, of the Union Oil Company of California, for his data on future LPG potentials. ★ ★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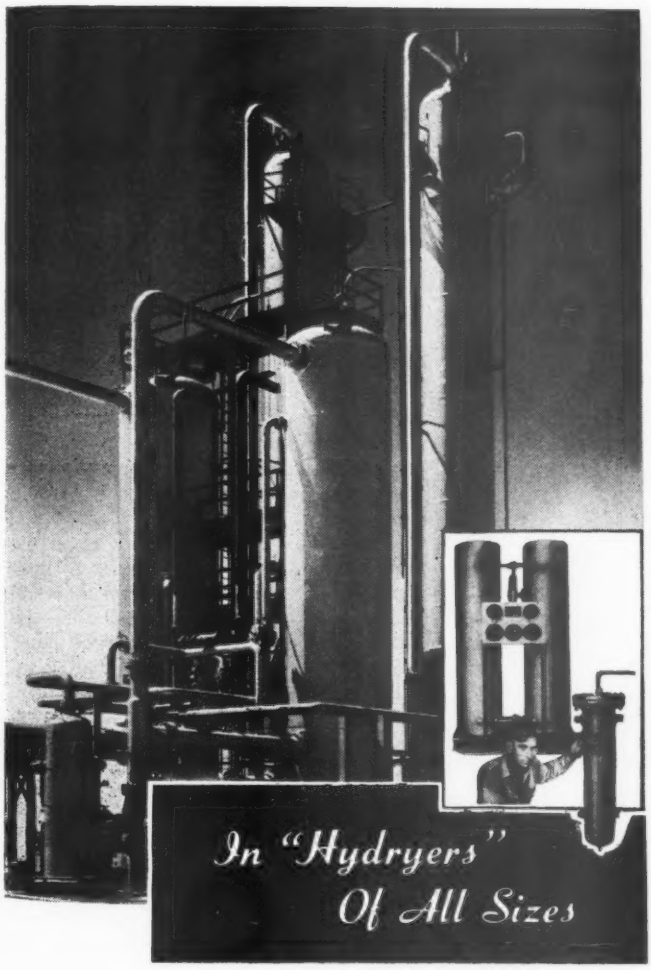

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Recent developments in pipeline technology*

By H. H. ANDERSON, Shell Pipe Line Corporation

● **Abstract.** The year 1941 witnessed the American pipe-line industry serenely handling its business with 132,000 miles of lines in service. The enormous demands of World War II for additional domestic overland transportation of crude oil and products required not only the construction of new large lines, but also the operation of existing lines at remarkable new throughputs. Furthermore, the demands of the armed forces for at-the-front pipe-line service were met with distinction.

This paper recites briefly the many noteworthy developments in pipe-line technology that made these feats possible. Applicable to the older lines are discussed increased line capacities, improved customer service, other improved operating techniques, and improved maintenance methods. Discussed also are newer construction methods as well as trends in new line design.

The paper should provide operators with a useful list against which to check the state of development of their own systems and their fitness to meet competition of new large lines in the tight economic period ahead.

RECENT is what you make it, so we're going to review wartime as well as postwar advances in oil pipe-lining. We need go prewar only to observe that producers, refiners, and marketers for 75 years have vied without stint to catch the public eye. Meanwhile pipeliners, like other subterranean life, were kept out of sight and mind.

Then came World War II with its headlines—"Pipe lines and railroads prevent field shutdown"; "Big Inch lines span half a continent to keep refineries going"; "Product lines supply vital war markets"; "Portable pipe lines make mechanized warfare practical"; "Pipe line across Channel serves invasion army"; "Indo-Burma pipe line relieves China"; etc. True, the public also heard of 100-octane, toluol, and butadiene—but in petroleum it turned out to be a pipeliners' war! That's a recent development I am proud to review! But we must fervently pray that the publicity will not boomerang and make pipe lines even worse political footballs than prewar.

In discussing domestic pipe-line "developments," we shall avoid wishful thinking, and shall postpone further reference to WEP's Jumbo and his bride because Pearl Harbor found us with about 132,000 miles of Not-So-Big Inch lines on hand to fight the war. These were modified and pushed to remarkable new efficiencies. Perhaps some of the techniques then developed can be profitably applied today—in fact, most of us can benefit from hearing of another's experience. In the time allotted we can present little more than a layman's listing of the many noteworthy developments that have come to our attention.

● **Improving older lines.** Increased line capacities. The sinking or transfer of tankers forced immediate steps to increase capacities of existing lines. With but little new pipe and few prime movers or pumps available, we taxed our ingenuity for methods to raise throughputs with equipment on hand.

Looping lines: An obvious first method was the old one of adding pipe loops to our trunk lines. Most of the pipe used was taken from abandoned lines or wells, or was purchased second- or third-hand from junk dealers. Some of the loops were added as reserve crossings at rivers, thereby increasing line capacity not only in the orthodox way, but also through adding insurance against prolonged interruptions during flood-time breaks.

Pipe-resistance reductions: The maintenance of pipe walls free of wax or other deposits received much attention. Our distinctive "go-devil" or scraper has been improved in many ways. Neoprene disks and wire brushes have replaced hard-rubber disks and knives. On the larger scrapers, life of disks has been increased by building them around a hollow air-tight cylinder for buoyancy and by drilling angular holes through them to cause rotation in transit. These holes also enable the oil slip streams to flush the débris ahead of the scraper.

Station capacity increases: Station capacities were increased in many ways. In centrifugal pumps the casings were bored out, and the impellers were built up and rebalanced to raise deliveries 5 to 10 per cent. In reciprocating pumps the cylinders were fitted with oversize liners and plungers and—where possible—run at higher speeds. Motor-power outputs were stepped up far beyond normal ratings, and some engines were supercharged to develop the needed extra power.

Stream viscosity reductions: By injecting field gasoline plant products into crude oil streams, the stream viscosities were lowered, with resultant higher daily throughputs at normal station pressures. Adding greater amounts of light products during winter months minimized the seasonal throughput decreases. Some crude streams regularly carried as much as 12 per cent of such "volatiles." Refiners benefited greatly because the light fractions were valuable in the manufacture of 100-octane gasoline.

● **Improved customer service.** The war-accelerated quest for ways to better serve the customers has borne fruit in many ways.

"Closed" crude oil lines: The advantage of operating crude oil lines without station float tanks is more and more realized. True, such operation in some instances has reduced their capacities as compared to the hoary practice of "putting and taking" into and out of station tanks before and behind each more-viscous batch of oil, but reductions of evaporation and inter-batch contamination are attained as offsetting benefits. Batch interfaces can be readily followed through the lines by use of gravitometers or, in product lines, by visual color comparison. Crude-line slowdowns due to "closed" operation can be minimized by controlled blending or injection of "volatiles."

Field segregation and blending: As an aid to refineries overtaxed by war demands, improved segregation of various crudes and the controlled blending of others close to their origins not only simplified distillation processes, but also reduced the number of refinery tanks required to assemble the several required charging stocks. Usually the pipe-line operator was able to render this aid with little or no increase in plant or cost.

Running direct to refinery topping units: As another outcome of controlled blending in the fields, it was found practical to run the crude oil streams from pipe line direct into the topping units. This practice also avoids evaporation losses of light or volatile-laden crudes from refinery stock tanks. Such line-to-still operation requires the pipe-line operator to keep the delivered stream uniform in quality and reasonably free from water. The refiner must be continuously informed of possible changes in stream composition. This is determined by locating at the pipe-line station immediately upstream such tell-tales as continuous vapor-pressure recorders, water detectors, automatic samplers, and gravitometers.

Delivering products uncontaminated: Advances have been made in reducing contamination or intermixing of adjacent batches in products lines. Further attention to choice of valve locations and elimination of dead spots has been found imperative. Some operators use

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*Presented before the Twenty-sixth Annual Meeting of the American Petroleum Institute, Chicago, Illinois, November 13, 1946.

†Chairman, API Topical Committee on Pipe-Line Technology; Shell Pipe Line Corporation, Houston, Texas; assisted by J. E. Mims of Shell Pipe Line Corporation, and suggestions by members of Topical Committee on Pipe-Line Technology.

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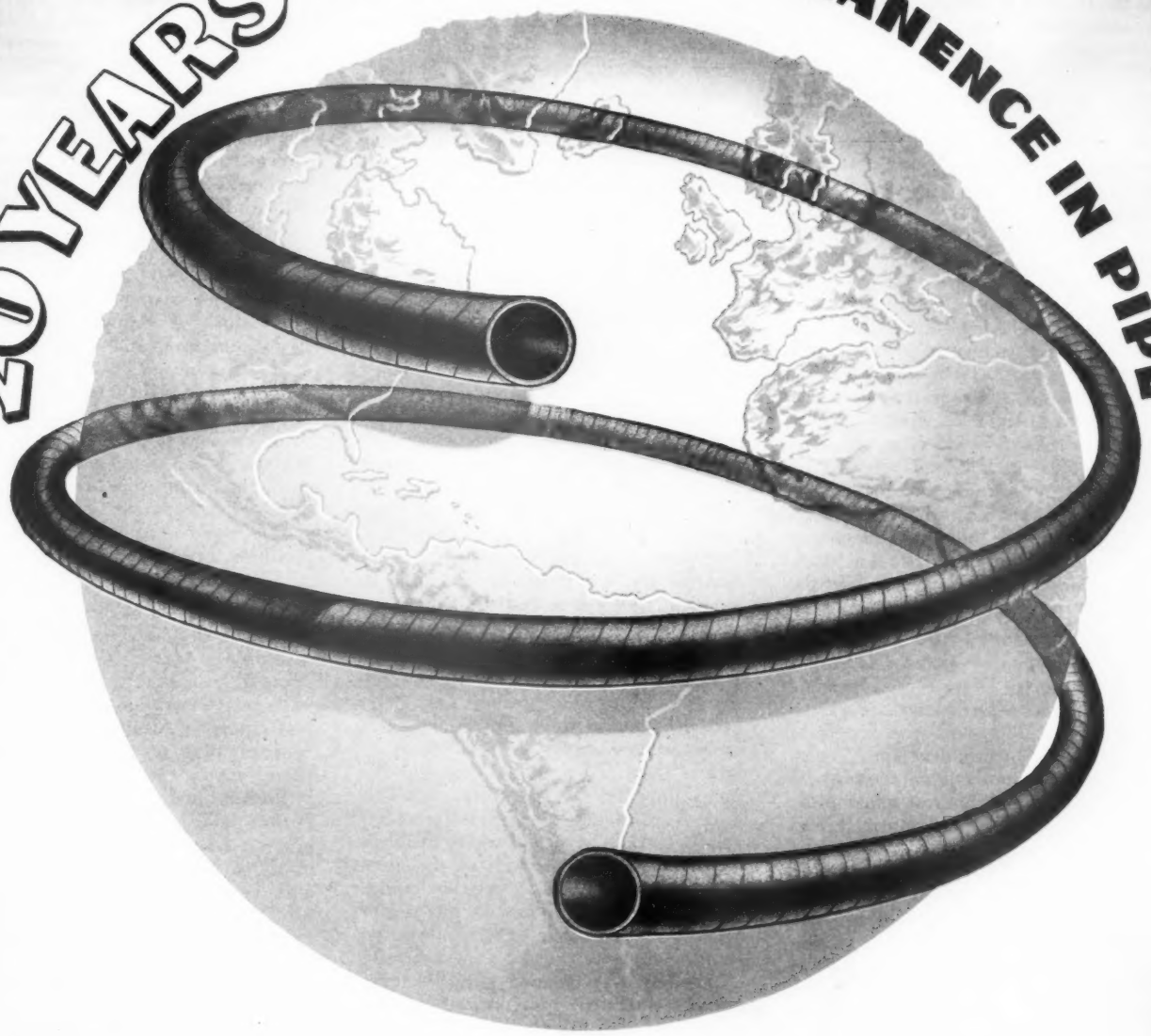

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synthetic rubber plugs, water slugs, or neutral buffer stock between batches, but the trend is to discard these in favor of direct contact and keeping the stream moving above the "critical" velocity and under full line pressure at all times. Excellent results are being obtained by this technique.

In line loops the problem of avoiding contamination due to varying flow rates in parallel sections has been solved by manipulation of a valve to equalize pressure differentials across orifices in the two sections.

Blending ethyl fluid into gasoline streams: Continuous blending of ethyl fluid into unleaded gasoline streams is another service performed by some products-line operators. To do this, a complicated mechanism is required. However, as to its principle of operation, the weight on a beam scale is moved by a small motor clutched and released by differential pressure created by the flow of untreated gasoline through a venturi tube located in the pump station suction line. The movement of the beam actuates valves to inject the ethyl fluid into the stream at the proper rate.

● **Other improved operating techniques.** The pipe-line operator as well as his customers are better served by some of the practices just described. However, other techniques of most benefit to the operator also were developed.

Dispatching and communication advances: The dispatching of many pipeline systems has been simplified and expedited by the increased use of telephones and teletypewriters. Telegraph dispatching is becoming "horse-and-buggy" stuff! Radio now provides two-way communication with personnel in isolated or scattered gathering systems, thus enabling closer contact of dispatchers with field men. Mobile or stationary FM (frequency-modulation radio) units and walkie-talkies now are common links used to speed up field operations.

During the war the extension of radio communication in private business was drastically curtailed; however, the Federal Communications Commission has since recognized pipeliners' rights to full use of this valuable tool. It has set aside appropriate bands in which wave lengths will be assigned to operators on proper application.

Carrier currents superimposed on telephone or telegraph circuits are used to perform the new techniques known as "telemetering' and "telegaging," i.e., the long-distance transmission of pressures and other meterable characteristics. These are adapted to keep dispatchers constantly informed of pressures and flow rates at distant terminals, booster stations, or pressure-control points. Line breaks or other failures thus show up immediately in the dispatchers' offices as unreconciled pressure changes or as discrepancies between line receipts and deliveries.

Fluids meter advances: "Closed" line operation, with its beneficial movement of volatile liquids, reduction of storage tanks, and minimizing of evaporation losses, requires that streams be metered. Abrasive foreign material in most crude-oil streams limits the use of positive-displacement meters, although improvements are being developed to overcome this handicap. Inferential (throat or orifice) meters of various types thus are used extensively on crude lines for control data. Positive-displacement meters are gaining wide acceptance on products lines and in marketing terminals, but they have been at a disadvantage due to lack of an accepted code of practice. The new tentative *ASME-API Petroleum PD Meter Code*, just now available for distribution, eliminates this deterrent. It culminates five years of work by a joint committee of oil-company engineers, meter manufacturers, and professional staff.

Automatic station development: With labor costs at an all-time high and the possibility of a shorter work week in sight, further development of unattended automatic booster stations moves ahead. Necessary control equipment now is hard to get, but it has been proved in service, and on future installations should be even more reliable.

Mobile pumping units: Greater use is being made of mobile main-line pumping units. Many older stations were stripped of standby units that were reset either on new lines or as boosters on enlarged lines. To provide some standby for station failure, portable main-line units were mounted on skids for emergency service when or where needed. This development, as well as the demonstrated reliability of regular equipment under high load factors, has taught operators that much expensive station standby equipment can be economically eliminated. Use of such portable units permits periodic overhaul of regular equipment, and fills the breach in emergencies. Permanent foundation slabs and manifold connections at each station enable units transfers to be made with little time loss.

Tank-suction booster pumps: Many oil storage tanks worth a dollar per barrel of gross working capacity are reduced in efficiency by adverse topography, long suction lines, or high bubble point of the crude. Automatic electric-powered pumps, both centrifugal and axial-flow, now are available that can be installed to advantage in the suction lines at low cost and with little disturbance to the piping.

Engine fuel improvement: Use of run-of-stream crude oil as diesel engine fuel in main-line stations is convenient. But many crudes make poor fuel due to their content of sulphur, suspended solids, carbon residue, asphalts, and gums that cause corrosion and abrasion of engine parts and dilution and contamination of lubricating oils. Entrained water often causes unsteady operation or stalling. Some operators are stopping such troubles by local "refining" of the crude to produce suitable fuel.

Gathering system improvements: Gathering systems have suffered long from a general lack of planning and sound engineering. Most of them, like Topsy, just grew. In newer fields, however, they are getting preferred attention. Main arteries are being made larger, laid to trunk-line specifications, and graded for gravity flow. Lateral lines are being designed of welded steel for sweet crude service, of cement-asbestos or cement-lined pipe for sour crude, and all with facilities for scraping when necessary. There is a general trend toward standardization of lease-tank battery headers and field pumping units. The use of time switches, interval timers, automatic tank shutoff valves, pressure flow regulators, and other controls on field pumping units serve to increase efficiency and reduce costs.

Better fire-fighting equipment: Most of us have some protection against fire, but recent developments of water fogs and other improved fire-fighting methods and equipment indicate that we should make a careful check of present facilities for efficiency and economy.

● **Improving maintenance methods.** The importance of preventive or corrective maintenance has been magnified manyfold, because it has been almost impossible to obtain delivery of repair parts or new equipment.

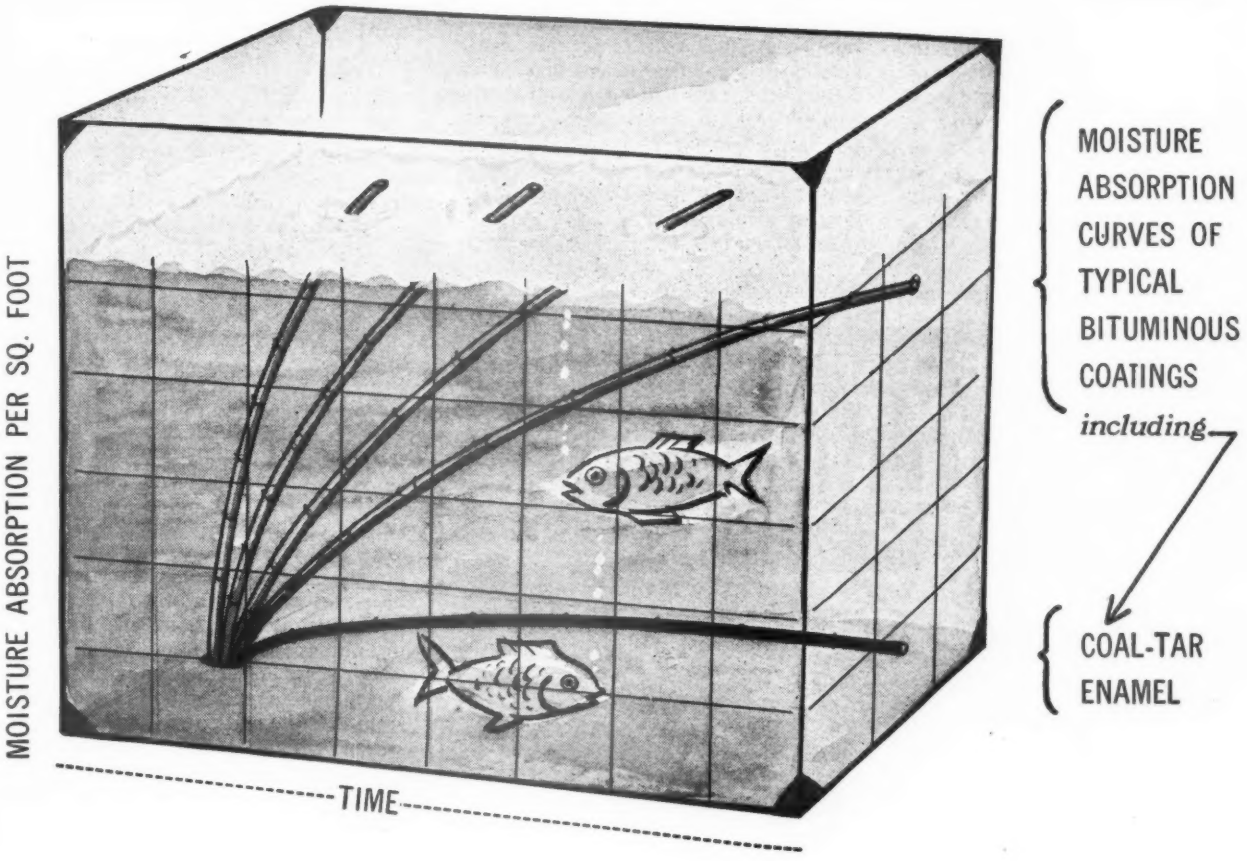
Air patrol: Although the writer's oil company was the only one to use air patrol during the war (beginning early in 1939 and flying with two planes about 16,000 miles regularly each month), postwar has witnessed wide acceptance of air patrols for detecting leaks, washouts, or line exposures along rights-of-way. Personnel transportation, mapping, construction, maintenance of telephone lines, and general inspections of line conditions also are simplfied by use of airplanes. On weekly inspections of crude oil trunk lines, one air-patrol plane can perform the job of about 25 line walkers for one-fourth of the cost (about 20 cents compared to 85 cents per mile). The patrols have proved equally effective in leak detection, with a decided advantage where they occur at river or creek crossings. Gathering system patrols are not generally practicable because of their general layout and the presence of a maze of other lines.

On products lines the patrol has proved unsatisfactory for leak detection. Product leaks are difficult to observe from the air, besides which at large ones there is danger (caused by gasoline fumes in an explosive mixture with air) to planes flying above them at hedge-hopping altitudes. The airplane is useful on product lines, however, for periodic or special maintenance inspections.

Corrosion control: Corrosion continues to be one of industry's most serious problems. Many of the older trunk lines, badly deteriorated from soil corrosion, are being reconditioned and given new protective coatings supplemented with cathodic protection.

Gravity lines of steel pipe used for

Stable Electrical Insulation



Barrett Coal-tar Enamels, because of their resistance to moisture absorption, provide an efficient electrical insulation over long periods of time.

Their high dielectric strength makes cathodic protection economical. Aware of this, engineers are today designing corrosion-proof pipelines, using protective coatings which have high electrical insulation values and require less current and equipment per mile of pipeline to make cathodic protection economical.

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gathering in certain sour-crude fields on intermittent or low-velocity flow (less than 2½ ft per sec) have a normal life expectancy as short as two years. Frequent scraping to remove accumulated brine and primary corrosion products has more than doubled their service life. Use of cement-asbestos pipe in such service is increasing, one such line being in fine shape after 10 years of service. Cement-lined pipe should give more comparable service for higher pressures if the joints are properly sealed. Work is in progress to develop injected corrosion inhibitors for crude oil lines, but the results cannot yet be appraised.

Products pipe lines have their own variety of internal corrosion. Data on very effective injected inhibitors have been widely publicized. Other measures, notably dehydration of product, have reached the stage of commercial use.

Internal corrosion of the upper parts of tanks by sour-oil vapors is receiving vigorous attention. Most of the war-developed lacquer surface finishes available carry a volatile solvent that leaves defects in the film when it evaporates. Several coats of the lacquer are necessary for a perfect seal. The "experts" say that to be successful the film must be produced by oxidation, polymerization, or condensation.

As to coatings for buried structures, many refinements in application now give a better job than heretofore and assurance of almost complete protection for many years. In supplementary cathodic protection of trunk lines, the use of rectifiers is developing as the general practice. For protection of tank bottoms and shorter lines, sacrificial anodes of magnesium or zinc seem preferable; in fact, under favorable conditions they show a very low cost.

The tank car was first used on American railroads on November 1, 1865, loading at Titusville, Pennsylvania, where the first oil well had been opened about six years before. It was a flat car fitted with two wooden tanks shaped like inverted tubs.

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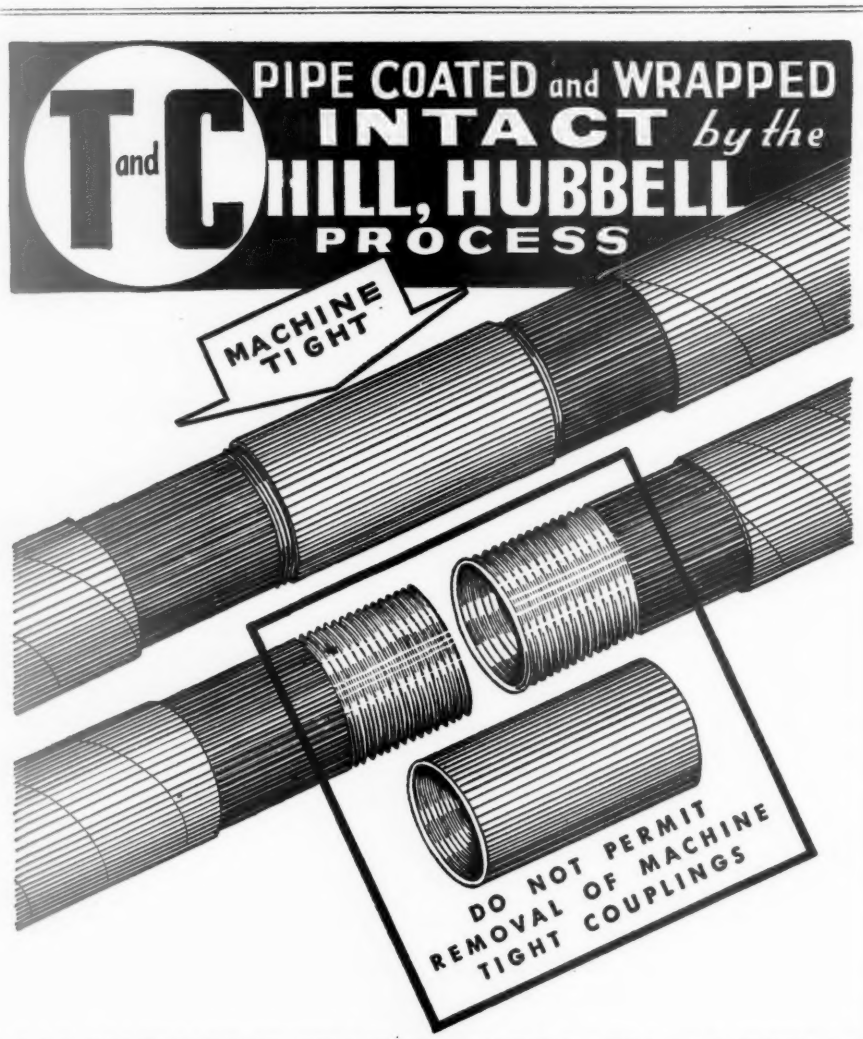
Line reconditioning: This has become one of the largest, if not the most important, maintenance jobs of the industry. Many vital lines were laid 20 or 30 years ago when corrosion was not understood. The higher wartime line pressures caused numerous leaks and ruptures that disclosed the damage done to pipe walls by corrosion. Corrective measures are being taken at a rapid rate by many operators. Among the improved techniques recently found for this work is a "reclaimer," which in one rapid and continuous operation strips the earth from the line and forces the pipe to the surface without damaging it.

After a line has been raised, any of several methods may be used in reconditioning. Where damage is extensive, the pipe can best be removed to a central location for repair. Coating and wrapping may be done there or after the pipe has been tied back into the line. "Over the trench" reconditioning (with the line kept in service) is cheaper and faster. When badly damaged sections are replaced, the line, of course, must be shut down long enough to permit cutting out the damaged section and splicing in the new pipe. The equipment used in reconditioning is, generally speaking, not new; but many recent advances have been made to speed up and improve the quality of the jobs.

Emergency-line repairs: To expedite emergency-line repairs, truck-mounted repair units, with all necessary tools or facilities, are being used to reduce labor costs as well as shutdown time and oil losses. Improved pipe-tapping and plugging devices increase the efficiency of making cuts in both crude and product lines. Avoiding need for mud or asphalt plugs reduces contamination. These devices are of ancient origin but of more recent popularity.

Machinery maintenance: During the war, with little or no standby equipment in pumping stations, operating continuity records were established that reflect great credit to the maintenance personnel, and stand as an epic demonstration of their ingenuity. Much machinery and equipment downtime is caused by minor and easily correctible weaknesses. Con-



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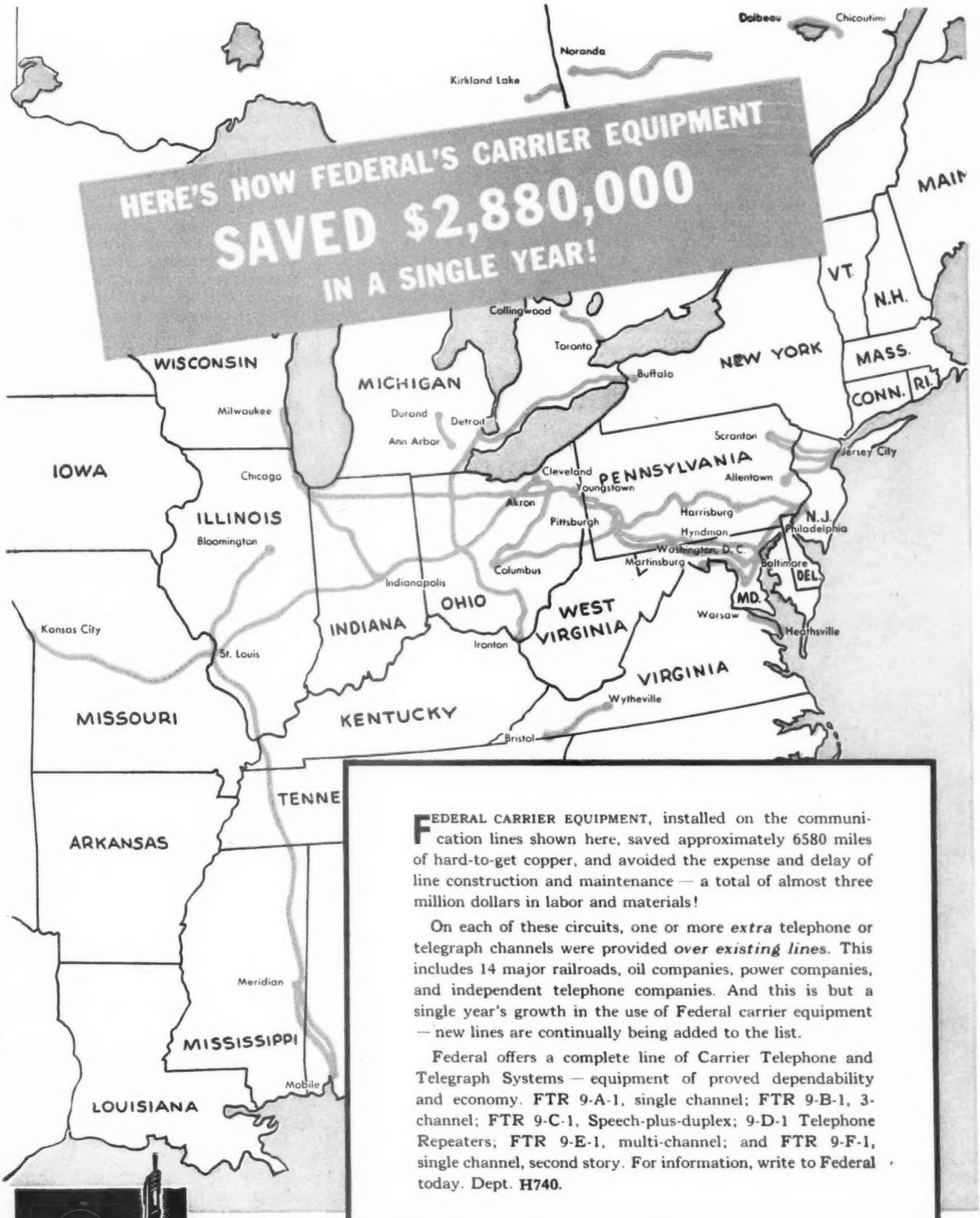

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sider, for instance, the conventional high-pressure plunger pump. Use of steel fluid ends stops the costly failures of cast iron. Light-weight alloy or micarta valves almost eliminate valve grinding and seat replacement. Packing and plunger replacements can be minimized by choice of plunger materials. Stainless steel (metalized on an iron base) or porcelain plungers wear 10 times as long as the best iron ones and show none of the characteristic grooving. But it took a war to awaken some of us to such now-obvious improvements!

● **Newer construction methods.** In line construction the development of new methods, or the complete acceptance of older ones, is apparent.

Aerial surveys: Use of aerial surveys to assist in the selection of pipe-line routes is "old stuff" for those who could afford it, but it has since become a "poor boy's" method as well, because contact prints covering large sections of the United States now are available at nominal cost from the U. S. Agricultural Adjustment Administration in Washington.

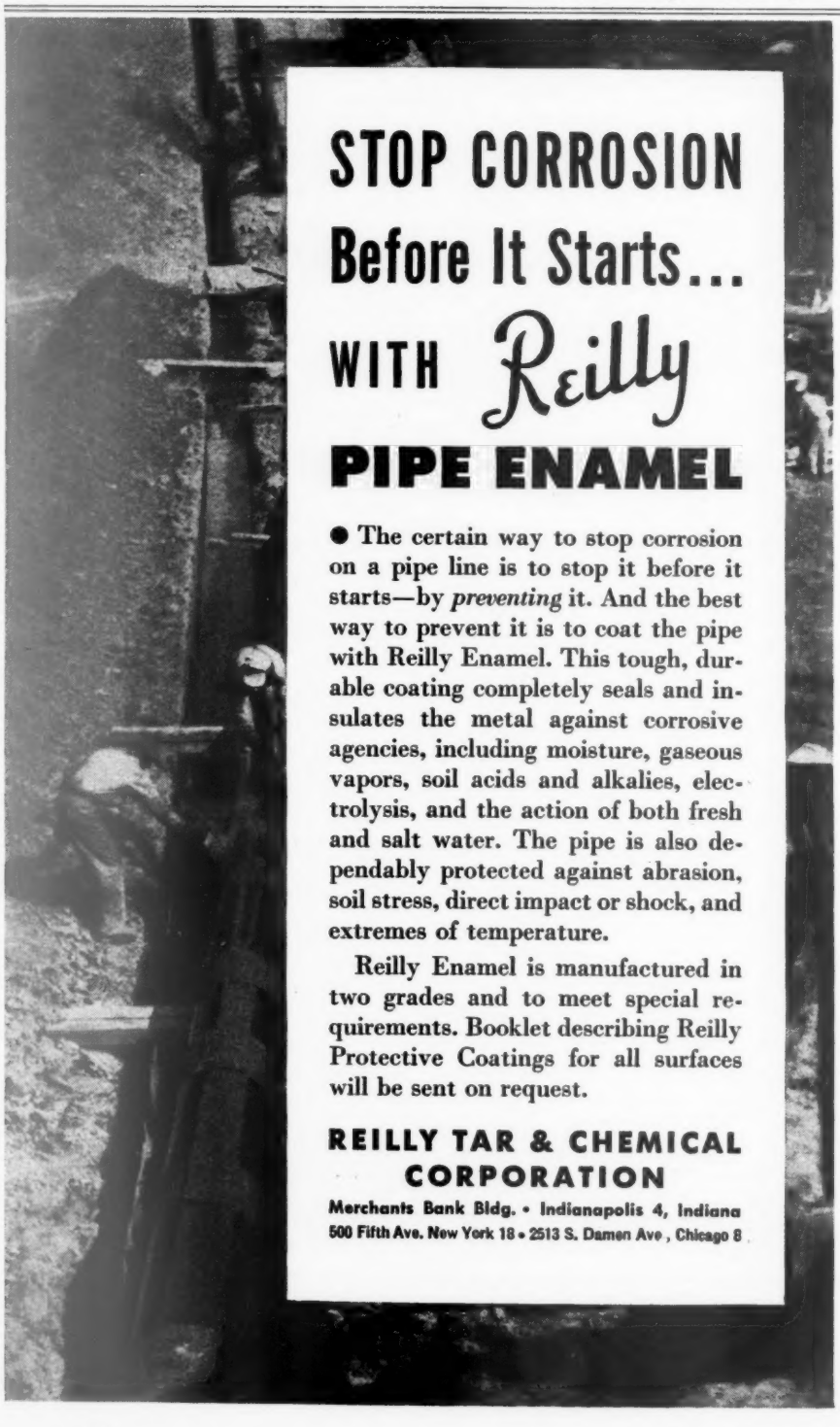
Pressure welding: "Pressure" or solid-phase welding has been used a great deal on recently laid lines. Speaking generally as to costs, arc welding is cheaper for pipe sizes up to 8 in.; costs are about the same for 10-in. pipe; and pressure welding is cheaper for larger sizes. The new technique is faster, and speed is a function of wall thickness rather than circumference. The joint strengths are as high or higher than the pipe wall if the welding is performed correctly.

Gamma-ray weld inspection: One organization reports the use of a gamma-ray inspection to insure good-quality field welds. It is done by wrapping a sensitized film in a light-tight container around the outside of the weld and inserting a radioactive element centrally in the pipe behind it. After a 15-min exposure, they are removed and a plug is welded into the small hole through which the element was inserted. The location, nature, and extent of weld imperfections show up clearly on the negatives and can at once be corrected.

Hydraulic line-up clamps: The distortion of big-inch pipe in handling and stringing has led to the development of a clamp that forces the abutting walls into alignment, and thereby aids welding. Users claim a decided increase in speed of laying the larger lines.

● **Trends in new line design.** I referred before to the WEP lines as Jumbo and his bride, neglecting to complete the metaphor by remarking that they are now our prize "white elephants." But, technically speaking, they are remarkable forerunners of a new era in pipelining. Designers of new lines are including many of the beneficial improved operating techniques already described, as well as newer equipment just now reaching the market in commercial quantities. In addition, they are benefiting by the Big Inch experience.

Larger pipe diameters: Experience has proved that it is more economical to obtain high throughputs by use of larger pipe than by increasing the number of stations or the line pressure. This is due partly to higher index costs of labor and machinery compared to costs of steel pipe. Even with the viscous crude oils of California, some operators are concluding that use of larger lines run at atmospheric temperatures are more economical than smaller ones in which the oil must be heated at each station. Thus, new and proposed lines of larger diameter are being designed with an eye to the future as well as the present. New lines probably will start operation at medium pressures or with extraordinary wide station spacing that will permit economical increases in pressure or number of stations to meet future needs. Increases in allowable fiber stress of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steel line pipe through use of high-grade alloys and cold working has made this possible.

Thinner pipe walls and telescoping weights: Improvements in pipe coatings and cathodic protection as a guard against soil corrosion, as well as higher strengths of the steel used, are permitting the use of thinner pipe walls. Nor do we need to use one wall thickness throughout a line because, by carrying the wall thickness in proportion to the hydrostatic head, we can save on the steel cost and yet keep a reasonable factor of safety.

Larger pump sizes: The increase in line size has required correspondingly greater pump capacities. The centrifugal pump has steadily gained popularity, even though it remains somewhat less efficient in energy consumption than the plunger pump. This popularity is due in part to low first cost and the special suitability of centrifugals for "closed" line operation. The old practice of connecting centrifugal pumps in parallel is now obsolete.

Improved pump design: Higher-speed triplex and quintuplex pumps are in use by at least one operator. Prime advantages are compactness and reduction of line surges. New vertical variable-stroke pumps are proving popular. By automatic or manual control, the plunger stroke of these can be varied from zero to a maximum while the pump is in operation. Their design, in effect, combines the flexible-volume characteristics of a centrifugal pump with the mechanical efficiency of the plunger type.

Engine design trends: Due to its flexibility and greater economy, diesel power still holds the advantage over electric power. Engine-design trends now, as in the past, are toward decreased weight-horsepower ratios and lower first cost. Increased reliability, compactness, operating economy, and ease of maintenance are prime objectives of the designers. The use of superchargers is increasing, and "dual-fuel" engines that run on various ratios of gas and oil are available. Closed cooling system, usually shell-and-tube heat exchangers, are replacing the less economical open types.

Improved general-station design: Piping manifolds are being placed above-ground to stop corrosion and make for accessibility. Station floors are being placed several feet above ground level to clear the manifold piping which is brought in through the floors to the pumps or instruments. Station buildings are being designed to perform their functions better. Noteworthy features are more convenient location of panels, engines, pumps, and auxiliary equipment; better ventilation and heating systems; noise-reduction treatments; and provisions for greater personnel safety. Even better lighting and proper contrast of colors for eyestrain reduction are not overlooked.

River crossings: For river crossings, more operators are using suspension

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bridges. For submerged lines the time-honored river "clamps" or weights are being abandoned in favor of welded sleeves to reinforce the pipe joints. Opinion varies as to whether buried river-crossing pipe should be coated, but the use of cathodic protection is general.

Speeded-up scraper handling: Greater use of scrapers in large lines has brought innovations in scraper spool and trap design. Injection is aided by use of slightly larger-diameter spools. Traps, built long enough to hold several scrapers, avoid the need to remove each separately. Traps made in diameter several inches larger than the line, and with small pipes tack-welded internally to center the scraper, reduce sticking and aid removal. For convenience, good housekeeping, and safety, the traps and input spools are being placed aboveground.

Electrical equipment: Electrical gear in pump stations has been steadily improved, and explosion-proof equipment is being installed almost entirely. The war forced the design of motors with less metal, but with no sacrifice in strength. Unitized transformer sub-stations now allow for better circuit arrangement. Forced-draft cooling of these has enabled them to carry greater loads.

As a means of avoiding shutdowns of electric-driven pumps due to circuit-breaker kickouts caused by power-line surges during storms, a manufacturer and an operator have cooperated to develop a quick-acting relay that will reset the breaker within 20 cycles (⅓ sec) of the kickout and before the motor slows down too much. This device should prove a blessing on "closed" lines, because at present the shutdown of one station often over or under-pressures the relays at the other stations—causing them to shut down also.

A major oil company has announced plans for the completion of a more than 3000-mile-long petroleum products pipe line system that will connect its refineries on the Atlantic Coast, Gulf Coast and Great Lakes region into a coordinated network.

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Tank farm design: Large tanks are being constructed of greater heights and smaller diameters to reduce the effects of inactive height and increase their volumetric efficiency. This design requires thicker shell sheets and heavier foundations to carry the increased pressures. Better devices for ground-level and remote gaging reduces earlier objections of gagers to high tanks. In tank farms, as at the newer stations, piping is being placed aboveground to good advantage.

The urge to conserve volatiles has developed methods of interconnecting groups of fixed-roof tanks with spheres or "balloons" which serve as gasometers. On many pipe lines, however, the floating-roof types of tank have proven to be the most flexible and efficient, with regard not only to vapor conservation but also to prevention of internal corrosion. A large number of older fixed-roof tanks have been or are being equipped with floating roofs.

● **Conclusion.** As was said previously, this paper is little more than a list of the noteworthy recent developments of our industry. We are offering it as a useful check list for all operators. The oil trade journals have been rich in fine articles describing fully most of these advances—readily available for the practical guidance of anyone who seeks to apply them to his own system.

Many of us can do little more than dream of building completely new systems. The mileage of new lines now proposed is insignificant compared to the mileage of lines that must remain in service. But, faced with the economic competition of some new larger lines, and placed between the rock of the Consent Decree and the hard place of further increases in labor and material costs, we shall be well advised to use all applicable improved techniques and get our houses in good order for the squeeze.

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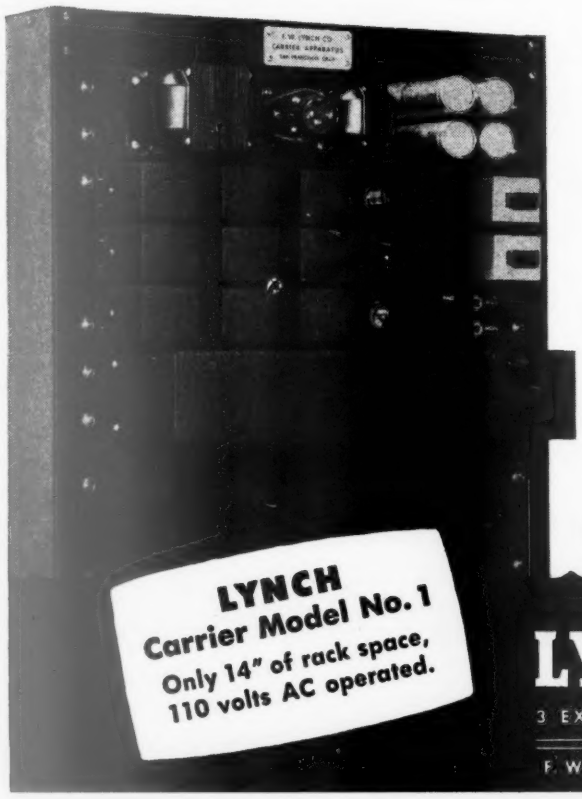

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Pilot pipe line unit for determining viscosity-temperature relationships*

By R. B. BECKMANN,† H. G. CORNEIL, and R. J. MICHAEL, Humble Oil and Refining Company

● **Abstract.** A pilot pipe-line unit and the experimental technique used in determining the apparent viscosities of high vapor pressure, waxy crude oil samples at various temperatures are described.

● **Introduction.** Reliable viscosity data for waxy crude oils at the lower pipe line operating temperatures cannot be obtained with conventional laboratory viscometers, because the wax crystals present in the crude cause irregular flow in tube or orifice-type instruments. Furthermore, excessive weathering of high vapor pressure crudes occurs in instruments of the Stormer or Macmichael type, commonly used to obtain viscosity data on heterogeneous fluids, during the relatively long period of time required to reach equilibrium at the low temperatures used. Since, in the past, these unreliable data were all that were available, it has been necessary to employ large safety factors in pipe-line hydraulics design calculations with the resultant overdesign and excessive equipment cost. As described in this paper, an apparatus of special design has been constructed and operated to obtain reliable viscosity data on waxy crude oils. The equipment used is a pilot scale pipe line unit; it requires an oil charge of approximately 20 gal for operation. It is believed that the experimental technique developed during these studies will be of considerable value to others confronted with similar problems. This paper describes the technique used and present typical data tained in measuring the apparent viscosities of volatile, waxy crude oil samples at various temperatures.

● **Description of pilot unit.** A simplified flow diagram of the pilot unit used for the studies is shown in Fig. 1; a more detailed diagram is shown in Fig. 2. The unit consists essentially of 60 ft of 0.314-in. ID KA2S seamless tubing through which the oil sample is pumped under measured, controlled conditions of temperature, pressure, and flow rate. The 60-ft test section consists of two straight 30-ft sections connected with a "U" bend. Each of the four pressure taps on the test section is 6 in. (19 pipe diameters) from bends, curves, and other flow disturbing influences to allow sufficient calming lengths prior to any given pressure reading. The entire test section is enclosed in a liquid propane constant temperature bath. The temperature of the bath is controlled by balancing manually controlled heat input from a steam heater tube with instrument-controlled refrigeration from another tube in which propane is evaporated. The pressure on the bath, corresponding to the desired temperature (bubble point of the bath liquid), actuates the instrument that controls the diaphragm valve in the liquid propane refrigeration supply.

The blend tank or reservoir has a capacity of 30 gal. This large volume was chosen to provide an adequate supply of oil for measurement of flow rates as well as to minimize fluctuations of the oil temperature in the blend tank. The oil sample after being charged to the unit is heated to 110 F and circulated through the entire unit, with the exception of the test section, for 30 min to insure complete mixing. The oil sample is then cooled to just below the lowest temperature to be studied, by circulating it through a jacketed coil that is cooled with manually controlled evaporating propane. When the desired temperature is reached, the oil is admitted to the previously described 60-ft test section. Immediately ahead of the test section is a 40-ft. section of ½-in. pipe that is immersed in the instrument-controlled boiling propane bath; this ½-in. pipe section provides final precise temperature adjustment.

During operation of the test section, control of the desired pressure drop across the section is maintained by controlling the pressure at the inlet of the section with an instrument that actuates a diaphragm valve in the bypass line

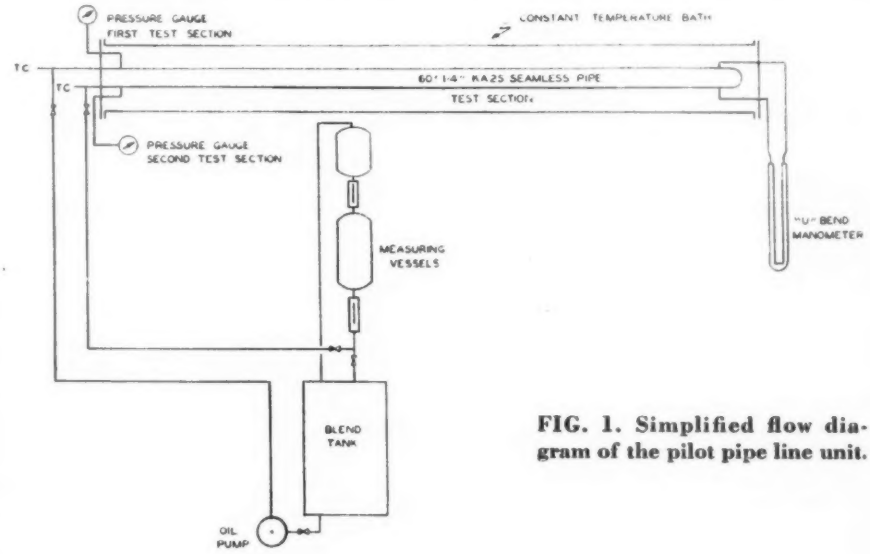

FIG. 1. Simplified flow diagram of the pilot pipe line unit.

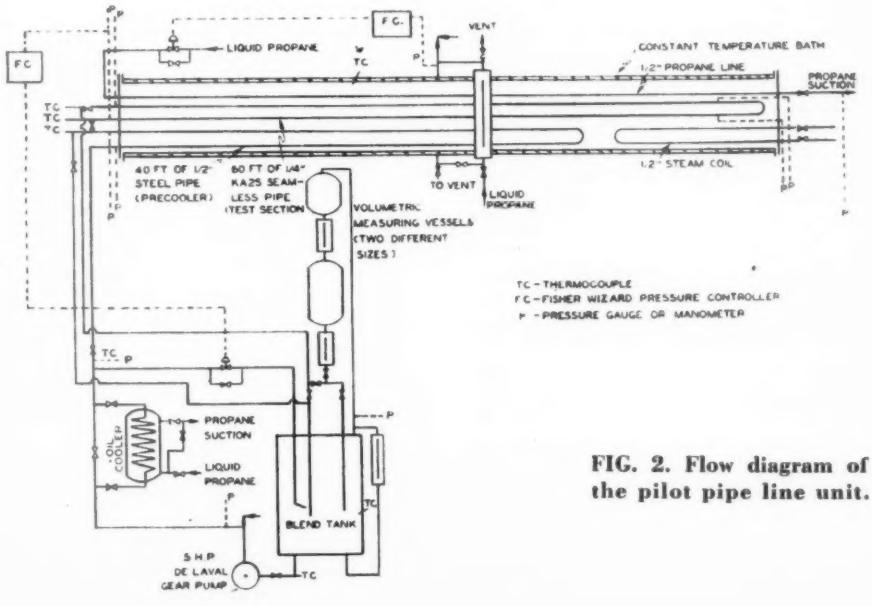

FIG. 2. Flow diagram of the pilot pipe line unit.

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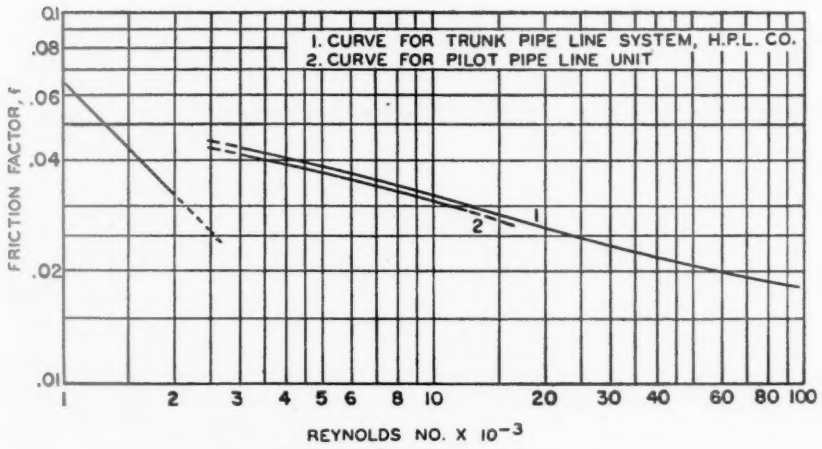

FIG. 3. Reynolds Number vs. friction factor.

between the pump discharge and the blend tank. Measurement of the oil flow rate is obtained by passing the effluent from the coil into either one of two calibrated measuring tanks of appropriate size. Pressures at the inlet and outlet of the test section are measured with duplicate, dead weight calibrated pressure gauges. A 50-in. mercury manometer measures the pressure drop across the return bend; this pressure drop is subtracted from the overall pressure drop across the test section to obtain the pressure drop across the 60 ft of straight pipe. All streams that enter the blend tank are delivered well below the top of the oil to prevent air bubbles being occluded in the oil. The entire unit is totally enclosed; as a result the oil sample can be maintained indefinitely without vapor loss.

Conventional iron-constantan thermocouples in stainless steel thermowells are used to measure the oil temperature at the inlet and outlet of the test section. Wax deposition on the walls of the test section is prevented by allowing heat to be transferred only from the outside of the pipe to the oil inside; thus during the study of any one sample, the temperature of the oil is increased as required from time to time, while maintaining the temperature of the bath that surrounds the test section above or equal to the oil temperature. In case it is necessary to reduce the temperature of the oil from check runs or for any other reason, the test section is cleaned before making the temperature reduction by circulating warm solvent naphtha through it and then blowing it dry with air. The solvent naphtha wash system is not shown on either of the flow diagrams.

During the study, it was found that the temperature control and circulating pump performance permitted viscosity determinations to be carried out on oils with viscosity values as high as 4100 Saybolt Universal Seconds (SUS). The DeLaval gear pump used to circulate the oil is rated at 12 gpm at 1725 rpm and can be operated at discharge pressures as high as 500 psig. Higher viscosity values could be measured by employing a pump with a higher discharge pressure rating.

● **Calibration and operation of pilot unit.** The pressure drop, friction factor, and Reynold's number relationship are used in calculating the apparent viscosity of the oil sample from the known and observed data such as pipe diameter, gravity of sample, pressure drop, and flow rate. Dewaxed or wax-free oils of known viscosity-temperature relationships were employed to establish the friction factor-Reynold's number curves for the 60-ft test section and thereby calibrate precisely the pilot unit. A plot of these factors is presented in Fig. 3. As would be expected, it was found that:

(a) In the viscous flow region, the curve corresponded precisely with the curve that is presented in various textbooks and handbooks. The relationship of Reynold's number and friction factor is not influenced by pipe diameter in the viscous flow region.

(b) In the turbulent flow region the position of the Reynold's number vs. friction factor curve was slightly different from the curves in the literature for pipes of average diameter and roughness.

The curves that were developed for the pilot unit were used in the subsequent determination of the viscosity of the waxy blends. Both viscous and turbulent flows were employed in making the viscosity determinations; data that fell in the critical region (transition between viscous and turbulent flow regions) were not used in establishing the viscosity

TABLE 1. Apparent viscosity determinations—pilot pipe-line unit experimental data.

Feed stock composition: Heavy Coastal gas. Laboratory viscosity, SUS=148″ at 70 F, 73.5″ at 100 F, 52.8″ at 130 F.
Laboratory inspections: Gravity at 60 F=26.9° API.

Run number	Net pressure drop, psi	Flow rate, gpm	Average temperature, F.	Friction factor, f	Reynolds number, N_{Re}	Apparent viscosity, SUS
1	95.2	2.757	81.5			110
2	69.3	2.283	86.0			98
3	35.8	1.228	86.5			95
4	60.1	2.757	103			75
5	77.6	1.954	74.5			124
6	68.1	1.685	75.5			126
7	37.9	0.968	75.5			123
8	16.1	0.444	77.5			117
9	74.8	2.670	87.5			92
10	74.0	2.730	89.0			90
11	74.2	2.790	90.5			88
12	88.7	2.330	76.0			120
13	17.6	0.464	76.0			120
14	79.3	2.700	85.0			96
15	42.0	1.500	85.5			92
16	76.9	1.420	62.0			166
17	50.1	0.960	62.5			160
18	16.5	0.305	63.0			171
19	97.4	1.190	52.5			249
20	97.4	1.190	52.5			249
21	124.8	1.080	44.5			349
22	123.8	1.080	44.5			346
23	185.2	1.070	37.0			522
24	186.9	0.710	27.5			790

Note: In this table and the following tables of the series, a friction factor and Reynolds Number will be indicated for only those runs in which flow is turbulent. For those cases where flow is viscous, these items are not necessary to calculate the apparent viscosity, however, the Reynolds Number is used to determine whether the flow is viscous, turbulent, or in the critica region.

TABLE 2. Apparent viscosity determinations—pilot pipe-line unit experimental data.

Feed stock composition: Dewaxed light motor oil. Laboratory viscosity, SUS=354″ at 100 F, 167.6″ at 130 F.
Laboratory inspections: Gravity at 60 F=30.1° API.

Run number	Net pressure drop, psi	Flow rate, gpm	Average temperature, F.	Friction factor, f	Reynolds number, N_{Re}	Apparent viscosity, SUS
1	107.4	0.364	68.0			917
2	47.4	0.163	68.0			908
3	37.4	0.184	79.5			635
4	53.5	0.273	80.5			612
5	138.5	0.723	81.0			601
6	134.6	0.925	90.0			452
7	76.1	0.543	90.5			440
8	32.3	0.227	90.0			447
9	137.1	1.295	101.0			335
10	64.9	0.644	102.0			320
11	26.7	0.262	103.0			322
12	120.5	0.0891	34.0			4100
13	103.5	0.1495	49.0			2100
14	104.2	0.234	57.5			1380

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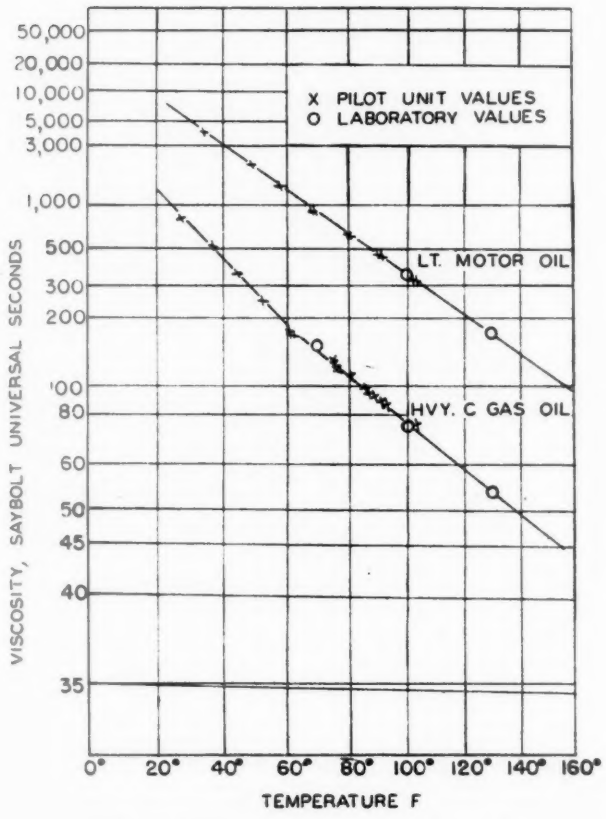


FIG. 4. Apparent viscosity of dewaxed light motor oil and heavy Coastal gas oil.

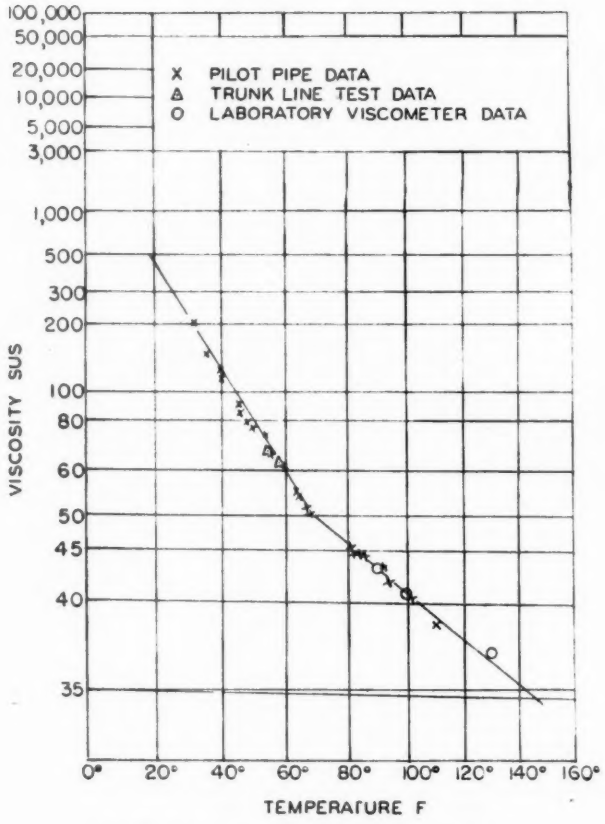


FIG. 6. Apparent viscosity of crude, December test sample 39.8 API.

characteristics of the sample. The turbulent flow region was, in general, encountered at temperatures above the wax point where corresponding viscosity values from laboratory viscometers were available. Both turbulent and viscous flow were encountered in the waxy region.

The validity of the pilot unit data for ideal fluids was established by comparing pilot unit and laboratory viscosity data on a dewaxed light motor oil and a heavy Coastal gas oil. It was demonstrated that the viscosity-temperature data calculated from the pilot unit data were in precise agreement with laboratory data obtained on conventional tube or orifice type viscometers. The viscosity-temperature data for the dewaxed light motor oil and the heavy Coastal gas oil used in this comparison are shown in Fig. 4; the data are tabulated in Tables 1 and 2. As the heavy Coastal gas oil exhibited waxy characteristics below 60 F, the data obtained below this temperature were not used in the comparison. The viscosity data obtained throughout these studies are plotted on *ASTM Standard Viscosity-Temperature Charts for Liquid Petroleum Products* (D-341-39) for convenience, since a straight line relationship generally exists for petroleum oils when the data are plotted on this chart.

To establish the validity of the pilot unit data in the waxy region it was necessary to compare the flow characteristics of a waxy oil in the pilot pipe-line unit with corresponding values observed on a commercial scale trunk pipe line. To do this, a series of tests was run on

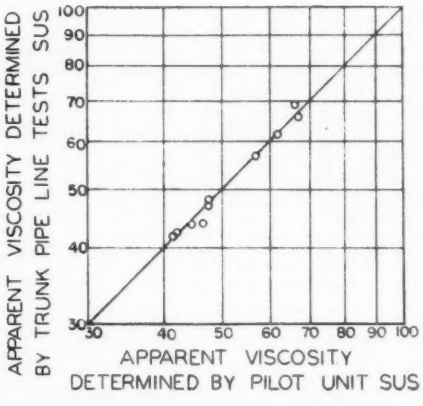


FIG. 5. Comparison of apparent viscosity values determined by pilot unit and trunk pipe line tests.

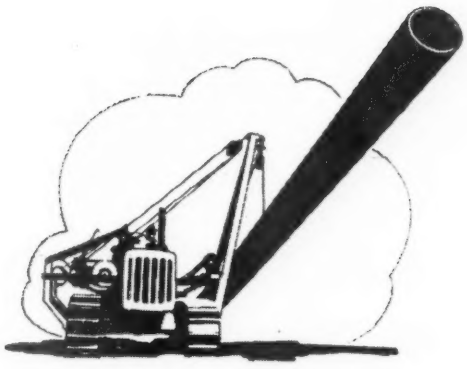
a 40-mi. section of Humble Pipe Line Company's 10-in. trunk pipe-line system, during which complete flow data were observed and composite samples of the crude flowing in the trunk line at the time were taken. A scraper was run through the trunk line immediately before each test was conducted to preclude the presence of wax on the walls of the pipe. From the flow data, the apparent viscosity of the crude flowing, at the operating temperature, was calculated. This value was compared then to an apparent viscosity value calculated from the pilot unit data obtained at the same temperature on the sample of crude collected during trunk pipe-line test run.

The ten test runs that were carried out on the trunk pipe line covered a viscosity range of 42 to 67 Saybolt Universal Seconds (SUS) at operating temperatures from 49 to 90 F. The apparent viscosity values obtained with the pilot unit on composite samples of the crude from each of the test runs agreed closely with the corresponding apparent viscosity calculated from the pipe line test data. A comparison of the pilot unit and trunk pipe-line viscosity values is presented in Fig. 5.

As good agreement was obtained between the pilot unit and trunk pipe line apparent viscosity values throughout the waxy as well as the non-waxy temperature ranges, it was concluded that pilot unit values were reliable. A further indication that the pilot unit values were reliable is that the apparent viscosity values obtained were identical at any given temperature over a broad range of flow rates regardless of whether the oil was waxy or non-waxy or the flow viscous or turbulent. This is contrary to the usual behavior of heterogeneous fluids.

● **Typical examples of data obtained on the pilot pipe-line unit.** To illustrate the accuracy and range of the data obtained on the pilot unit several examples of the data are presented.

In Fig. 6 and Table 3 are presented the data obtained on the pilot unit on the crude sample collected during the December, 1944, test run on the trunk pipe-line system. Fig. 6 illustrates both the agreement between pilot unit and laboratory values in the homogeneous region and the agreement between the



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apparent viscosity calculated from the pilot unit data and that calculated from the trunk pipe-line tests.

In order to investigate both the operable range of the pilot unit and the effect of increasing waxiness on the apparent viscosity in the waxy region, samples of residuums obtained from a waxy crude were blended in varying proportions with the original crude and the blends were evaluated for viscosity-temperature characteristics on the pilot pipe-line unit. In Fig. 7 are presented typical data obtained from several of these blends. The right-hand plot shows the apparent viscosity-temperature relationship for the actual blends and in the left-hand plot the data are cross-plotted to permit easy interpolation to any percentage blend at varying temperatures. The same ASTM chart used for expressing the viscosity-temperature relationships can be used for cross-plotting to viscosity-percentage relationships by using the portion of the ASTM chart between 0 F and 100 F and converting the temperature ordinates to percentage ordinates.

The above examples have been cited to illustrate but two of the uses for which this type of pilot unit may be employed. As previously mentioned, the technique and apparatus involved should prove useful for obtaining apparent viscosity values for use in hydraulic calculations for many high vapor pressure and/or heterogeneous systems wherein the conventional laboratory viscometers are not satisfactory.

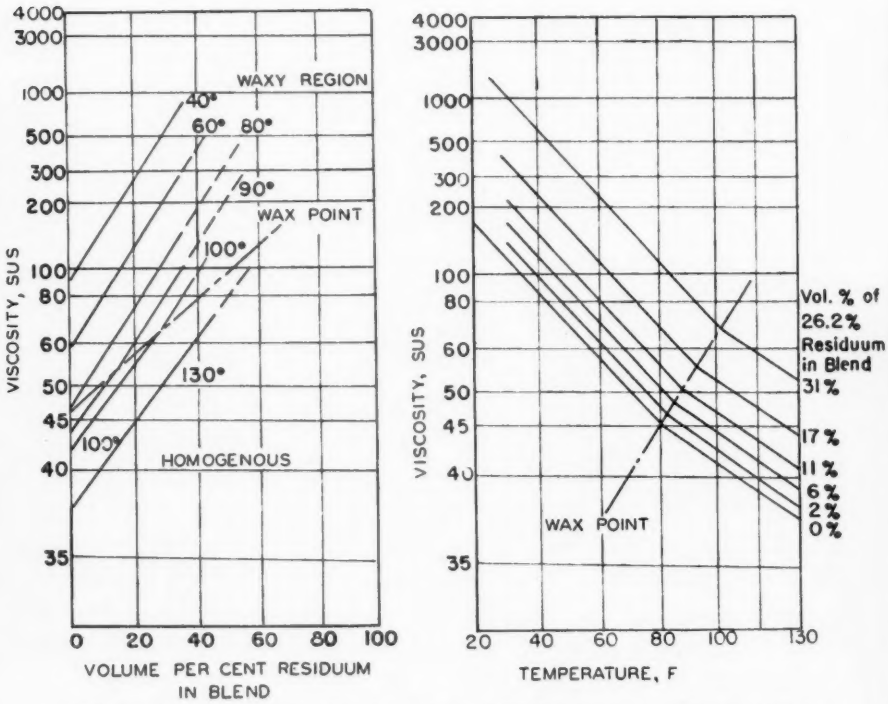

FIG. 7. Apparent viscosity of crude and 26.2 per cent residuum blends.

● **Appendix.**

The following is a resumé of the fluid flow equations used throughout this study:

1. Fanning equation for both viscous and turbulent flow:

$$P = \frac{flpv^2}{2g_oD} \quad \ldots\ldots \quad (1)$$

Where:

P = pressure drop, psf,
f = friction factor,
l = length of test section, ft,
p = density of fluid flowing, lb per cu ft,
v = velocity of fluid flowing, fps,
g_o = acceleration of gravity = fps^2,
D = diameter of pipe = ft.

2. Poiseulles law for viscous flow:

$$f = 64/N_{Re} \qquad P = \frac{64lpv^2}{2g_oDN_{Re}}$$

Where:

N_{Re} = Reynolds Number, using values in the units expressed in the above table and viscosity in (lb per sec) (ft).

3. Turbulent flow: From equation (1), Fanning equation, the friction factor was calculated from the test data.

The Reynolds Number (N_{Re}) was obtained from the calibration plot of f — vs — ϕ (N_{Re}), and the absolute viscosity in centistokes was calculated from the Reynolds Number. The viscosity values in centistokes were converted to Saybolt Universal Seconds by use of *ASTM Conversion Tables for Kinematic and Saybolt Universal Viscosities.*

● **Suspension of wax.** Wax crystals suspended in the oil are prevented from settling in the blend tank of the pilot unit by maintaining the flow rate of the oil that bypasses the test section of a maximum, thus insuring complete agitation of the oil reservoir. In commercial practice the trunk pipe lines are cleaned periodically with a mechanical scraper. The trunk line tests were run immediately following such a cleaning to insure each of the test's being run under known, identical conditions of inner pipe surface.

● **Apparent viscosity.** It was found during this study that the apparent viscosity calculated from the flow data was not dependent upon the rate of fluid flow through the test section at any given temperature level. If the waxy oils had exhibited the usual heterogeneous fluid characteristics, i.e., variation of viscosity with shearing rate, a different apparent viscosity would have been obtained with each flow rate employed at any given temperature. It must be borne in mind that no attempt has been made in this study to calculate a true viscosity, but rather an apparent viscosity value that can be used with some assurance in hydraulic calculations. It is not known whether the pilot unit could be used on fluids of known heterogeneous behavior and the pilot unit would have to be calibrated for such a material to determine whether the apparent viscosity values were accurate. ★★★

TABLE 3. Apparent viscosity determinations—pilot pipe-line unit experimental data.

Feed stock composition: Crude, December test sample, H.P.L. Co.
Laboratory inspections: Gravity at 60 F=39.8° API.
Laboratory viscosity, SUS=43″ at 90 F; 40.7″ at 100 F; 37.0″ at 130 F.

Run number	Net pressure drop, psi	Flow rate, gpm	Average temperature, F.	Friction factor, f	Reynolds number, N_{Re}	Apparent viscosity, SUS
1	78.4	1.240	32.0			206
2	103.9	2.340	36.0			146
3	87.0	2.400	40.0			121
4	93.8	2.820	40.0			112
5	82.8	3.440	46.0			85
6	67.0	2.550	46.5			90
8	56.5	2.870	55.0			73
9	57.9	2.520	64.0	0.0410	3000	54
11	17.6	1.438	64.0			54.5
15	100.5	3.605	78.0	0.0353	5700	46.7
16	65.8	2.875	84.0	0.0364	5000	44.8
17	75.0	3.110	85.0	0.0354	5600	44.2
18	56.6	2.665	92.0	0.0364	5000	43.5
19	45.3	2.390	93.0	0.0364	5000	41.7
20	57.8	2.765*	100.5	0.0347	6300	40.4
21	49.8	2.550	100.5	0.0352	5800	40.4
23	49.9	2.605	111.0	0.0339	7000	38.3
24	67.6	3.110	48.0			79.0
25	59.7	2.890	49.0			76.0
27	21.7	1.335	56.5			64.0
28	60.0	2.605	67.0	0.0398	3400	51.0
29	68.9	2.820	67.5	0.0392	3700	51.0
30	67.6	2.905	82.0	0.0364	5100	44.6
31	59.9	2.700	82.0	0.0374	4500	45.5

Runs 10, 13, 14, 22, and 26 were in critical region of Reynolds Number.

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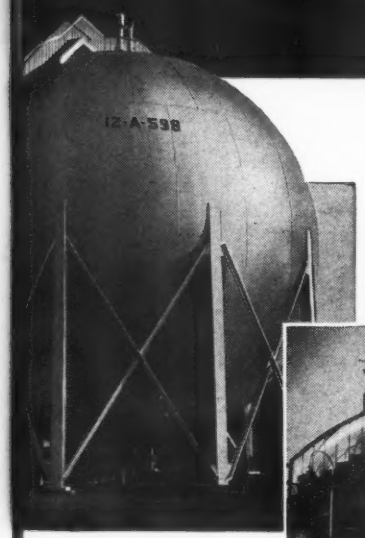

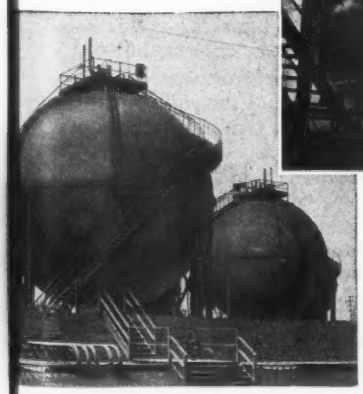

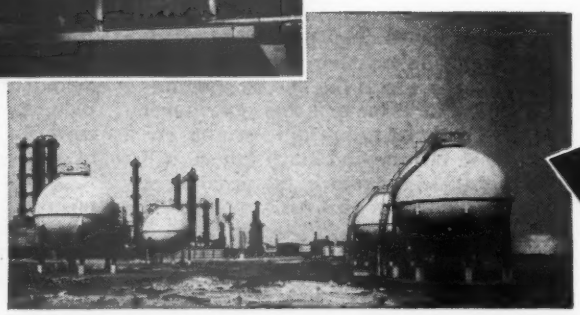

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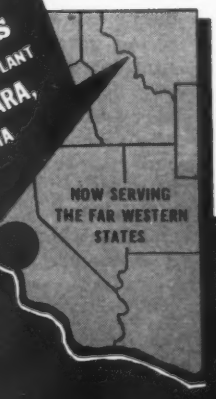

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P 615.635

Corrosion surveys

By M. E. PARKER, JR., *Corrosion Engineer*, Pan American Pipe Line Company

● **Introduction.** A survey has been defined as a "critical inspection to obtain exact information." The kind of survey we are here discussing, the corrosion survey, is a critical inspection of a buried pipe line and the environment in which it is buried, or of an environment in which it is proposed to bury one, to obtain information—but seldom exact information—concerning the various factors that may contribute, or which are contributing, to the destruction of that pipe line by its environment; information from which we may predict what is happening, or determine what steps may be taken to control what is happening.

The problem of protecting a buried pipe line from soil corrosion is basically different from all other corrosion problems that may confront the engineer. It differs from all the others not merely in degree, but fundamentally in kind. In the first place, the exposure is much more nearly total than in any other industry or activity. In a typical pipe-line system (an oil line, in this case) 64 per cent of the total investment in the system is in the line itself—64 per cent of the whole concern is exposed to destruction by soil corrosion. All other corrosion problems —atmospheric, water, lubricating oil, etc.—involve such relatively small areas of exposure that special treatments, special materials, expensive in unit costs, are economically justifiable. This type of solution, the selection of a "non-corrosive" material, is not available to the pipe-line corrosion engineer at present, nor is there any immediate hope for such.

Another basic difference is in the extreme complexity of the corroding agent. In any type of industrial process there is always the possibility of analyzing and understanding the particular agent responsible for corrosion, and thus planning a program for combating it. The only two environments that even approach soil in complexity are the atmosphere and water; both are actually much simpler and easier to cope with.

● **Two solutions to the problem.** There are, however, two theoretically perfect solutions to the problem of underground pipe corrosion. One is the application to the pipe of a protective coating. To completely prevent corrosion, such a coating must be absolutely impervious to moisture, have sufficient mechanical strength to resist the forces it will encounter, and be applied in an absolutely continuous and unbroken sheet. Two qualities usually prescribed for a coating are here omitted: That it be an electrical insulator, and that it bond firmly to the pipe. These qualities are only necessary when the others fall short of perfection. If absolutely no moisture can reach the pipe, then there is no need for an insulating coating. And if the coating is absolutely continuous and unbroken, then it is not necessary for it to be bonded or attached to the pipe. It is unnecessary to point out that no such coating has ever been produced, nor does it seem likely that one will appear in the foreseeable future.

A second theoretically possible perfect solution to the problem is the maintenance, by suitable apparatus, of a sufficient protective potential relative to the adjacent soil. There are many reasons why this is not always feasible. There is the inevitable problem of induced corrosion on nearby structures, with all its attendant complications. In many areas of low resistivity soil, the energy requirements for the maintenance of a protective voltage are prohibitively high; as high as 10 kw. per mile for a 12-in. line, with an investment in apparatus of $3000 or more per mile. If galvanic anodes are used, an almost solid wall would be required under the most unfavorable conditions, and the costs would be similarly high.

Actually, the vast majority of lines may be practically protected by an economic compromise between these two different methods. A coating is applied to the pipe, which is not entirely perfect, but is nearly so. It is a comparatively simple matter to coat pipe in such a way that less than 1 per cent of its total area is actually exposed to attack. When we have done this, the energy requirements for protection by potential become only one-one-hundredth of those for bare pipe. If the coating is much poorer than this, the protection costs rise rapidly; a coating very much better than 99 per cent is likely to be expensive. Somewhere in this neighborhood it should be possible to find the point of economic balance, if all the relevant factors are properly weighed.

Many of these factors do not properly lie within the scope of the corrosion survey itself; among these are the anticipated useful life of the line, the possible salvage value of the pipe, the opportunity to save costs by using thinner pipe, etc. All these factors, and many others, will have to be considered in the problem of design, but are not properly the subject of the survey itself.

The survey itself must supply the answers to certain questions, of which the following is an incomplete list:

(1) What rate of corrosion may be reasonably expected if a line is laid in this location?

(2) What kind and amount of protection would be effective here?

(3) How rapidly is corrosion taking place on this line?

(4) How much energy will be required to arrest corrosion on this line?

(5) How effectively is our protection program working?

(6) How rapidly is this coating deteriorating?

(7) Is our protection program adversely affecting some other structure? If so, how much? How may this be corrected?

In seeking useful answers to questions like these, we wish to determine a set of measurable quantities, and select the proper instruments with which to measure them, at a reasonable rate of speed, and with a reasonable expenditure of time and money. It is useless to attempt to measure every pertinent factor. The soil is far too complex for that. We must find a set of factors that can be measured rapidly and easily, and which together will give us a sufficiently good picture of the conditions.

● **Major types of surveys.** The various types of corrosion surveys may be classified according to their principal function; that is, the specific question whose answer is sought. This will of course depend to a large extent on when the survey is made, in comparison with the life of the pipe line in question.

First we may consider the preliminary or exploratory survey, made on the route of a proposed pipe line. It should be pointed out that rarely, if ever, is such a survey made the basis of determining the location of the line, although it may influence it slightly. Usually the location is determined by other considerations, and the route is already staked when the corrosion survey is made. What is to be determined is the kind and amount of protective coating to be applied at the time the line is laid, insofar as this is influenced by the physical environment.

The quantities to be measured here are the characteristics of the soil. Of all the various properties that might be determined, by far the most important is the electrical resistivity of the soil. A complete chemical study of the various soils traversed is out of the question, because of the complexity and variety of soils found. In addition, it has been well demonstrated that there is a very high degree of correlation between soil resistivity and rate of corrosion; in other words, all or nearly all of the many factors that combine to make a soil corrosive, also combine to make it a good conductor of electricity. There can be considerable discussion as to which is cause and which is effect, but the important and useful fact is that low resistivity soils are nearly always corrosive, and

*Presented at First Annual Short Course in Gas Technology, Texas A. & I. College, Kingsville, Texas, August 27-29, 1946.

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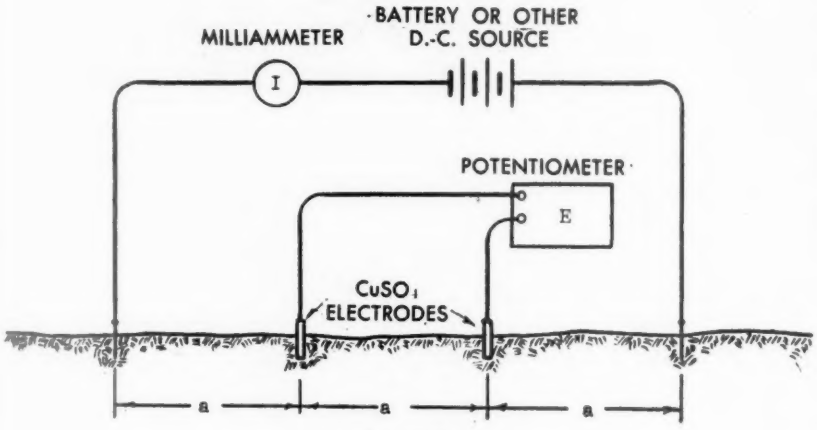
FIG. 1. Soil resistivity measurement
Four electrode—direct current



$\rho = 2\ \pi\ E/I$ where

ρ = resistivity in ohm-centimeters
a = electrode spacing in centimeters
E = potential drop in millivolts
I = current in milliamperes

Direction of current must be reversed and readings averaged, to eliminate errors due to stray currents in soil and accidental electrode potentials.

high resistivity soils are almost never corrosive. Still another reason for emphasis on this particular characteristic is that it is very easily and rapidly measured.

Besides this specific measured quantity, data should be collected on general topography, drainage, and the like. Rocky terrain causes severe abrasion on coatings; heavy clays, subject to alternate wet and dry conditions, impose soil stresses tending to tear the coating off the pipe; alternate hills and valleys mean alternate wet and dry sections; pipe-line crossings mean possible interference problems; electric railways mean possible stray current electrolysis. A wide variety of conditions that may affect corrosion should be located and noted in such a survey.

Another frequent type of survey is that conducted on a line already laid, either old or new. The same values mentioned above will be determined, and, in addition, others connected with the pipe itself. The information sought is that necessary for the determination of the kind and amount of protection the line will need, or for the prediction of its probable life without protection, or possibly for a decision as to whether it should be replaced, reconditioned, salvaged, or abandoned.

In addition to soil characteristics, there will be measurements of pipe-to-soil potential at appropriate intervals, and of currents flowing in the line. Both of these measurements have as their ultimate purpose the location of anodic (corroding) sections, their length and severity. Still another measurement that will shed light on this particular question is the determination of the current flowing through the soil in the immediate neighborhood of the pipe—or even the actual value of the current leaving the pipe. But these measurements are time-consuming and complicated, and to make a really complete survey of the whole length of a line would be slow and expensive. Anything less than a complete survey would be useless (except for research purposes).

If the line in question has been in service for several years, it will probably be necessary to make actual inspections of the pipe surface and the coating at selected intervals. These locations can best be determined after the completion of the electrical survey, so that it may serve as a check thereon. In order to make the check valuable, some sites should be excavated where the electrical survey indicates active corrosion, and some where no activity is suspected. In this way a good idea may be had as to the accuracy of the survey methods in their reflection of true conditions.

Sometimes, at this stage, it is desirable to measure the effective electrical resistance of the coating—that is, the circuit between the pipe and the "ground." Necessarily this includes several different resistances that are not easy to separate, but the differentiation between them is of more value to research than to a specific corrosion problem. This measurement is of value in estimating the amount of current necessary to protect the line, proper spacing of current sources, and the like, and will prove especially valuable when the same quantities are measured later, in estimating the useful life of the coating.

The third major type of survey is that conducted on a line that has been placed under protection. The purpose here is to determine the adequacy of the protection, to predict its future course, to check the deterioration of the coating, and in general to supervise and maintain the program. The factors measured are the same as those last mentioned, together with the output data on the protective units employed. A proper study of successive surveys of this kind, particularly pipe-to-soil potentials, will disclose local coating failures as well as indicate general decay. Local repairs of limited extent may prolong the useful life of a coating at a very reasonable cost, when the locations are correctly chosen.

For the specific purpose of determining the condition of pipe coating, an instrument is available that almost completely isolates this factor from all the complicating and confusing influences usually encountered. This is done by imposing between the pipe and ground a high frequency voltage. Even with a perfect coating, current will flow, because of the condenser effect of the two conductors (pipe and ground) separated by the dielectric coating. This current flow will be much greater through any defect in the coating that allows moisture to contact the pipe directly. All current flowing from the pipe to ground must return to the ground rod of the instrument, and in so doing sets up a potential field in the ground. In general, the voltage drop along the surface of the ground will be much greater where the current flow is concentrated, although this effect will be somewhat masked by variations in earth resistivity. It is this voltage drop along the surface of the ground that is detected and measured in the operation of the device. It gives excellent results on a good coating with a few defects, but not so good on a generally poor coating. It is most useful when successive surveys are run under similar conditions on the same section of pipe.

Besides the three major types of surveys enumerated, there are a number of special surveys of more limited scope for specific purposes. Surveys may be run for determining suitable sites for anode beds, taking into account moisture, soil resistivity, accessibility, power supply, and land availability. In the use of galvanic anodes, after the general distribution has been determined, exact locations must be determined by some sort of survey. In cooperation with other companies, studies must be made of the interference effects of protective systems on each other and on various foreign underground structures.

Not exactly surveys, but certainly closely allied, are the various opportunities that arise from time to time as sections of the line are uncovered for new connections, highway construction, crossing lines, etc. At such times inspections and measurements can be made with little expenditure of effort, and no such opportunity should be allowed to escape.

● **The component elements of corrosion surveys.** It will be observed that many of the various types of surveys have certain elements in common. It may perhaps be useful to examine these various elements separately, without immediate consideration of the precise type of survey in which they are to be used. These elements may be conveniently classified

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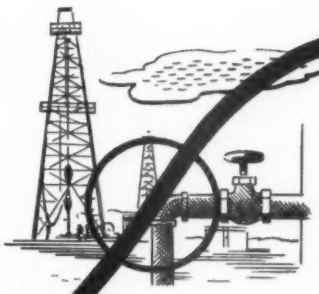

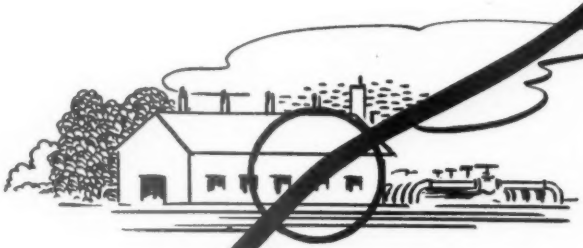

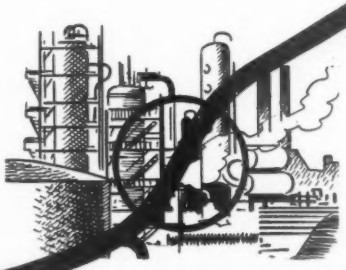

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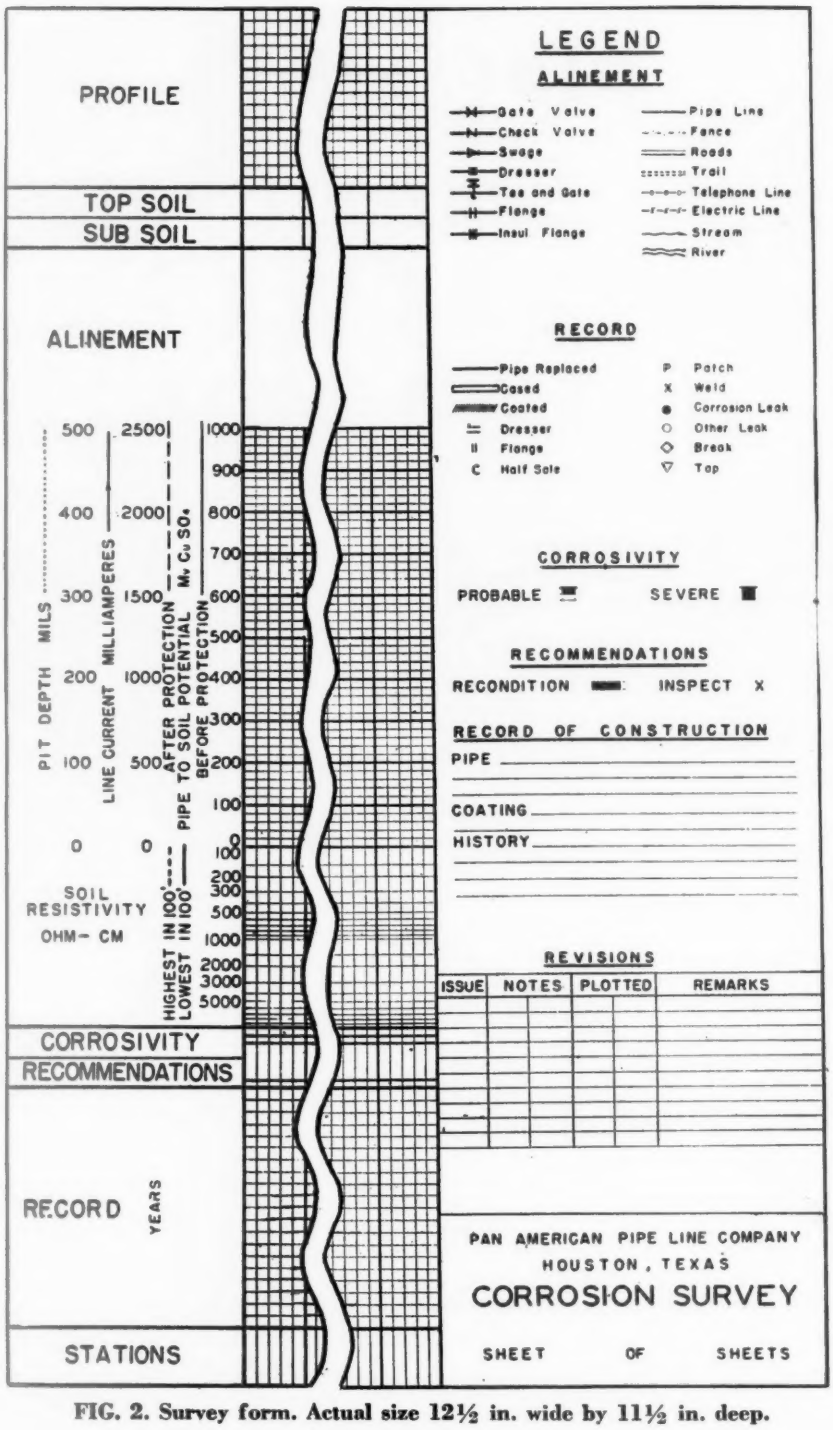


FIG. 2. Survey form. Actual size 12½ in. wide by 11½ in. deep.

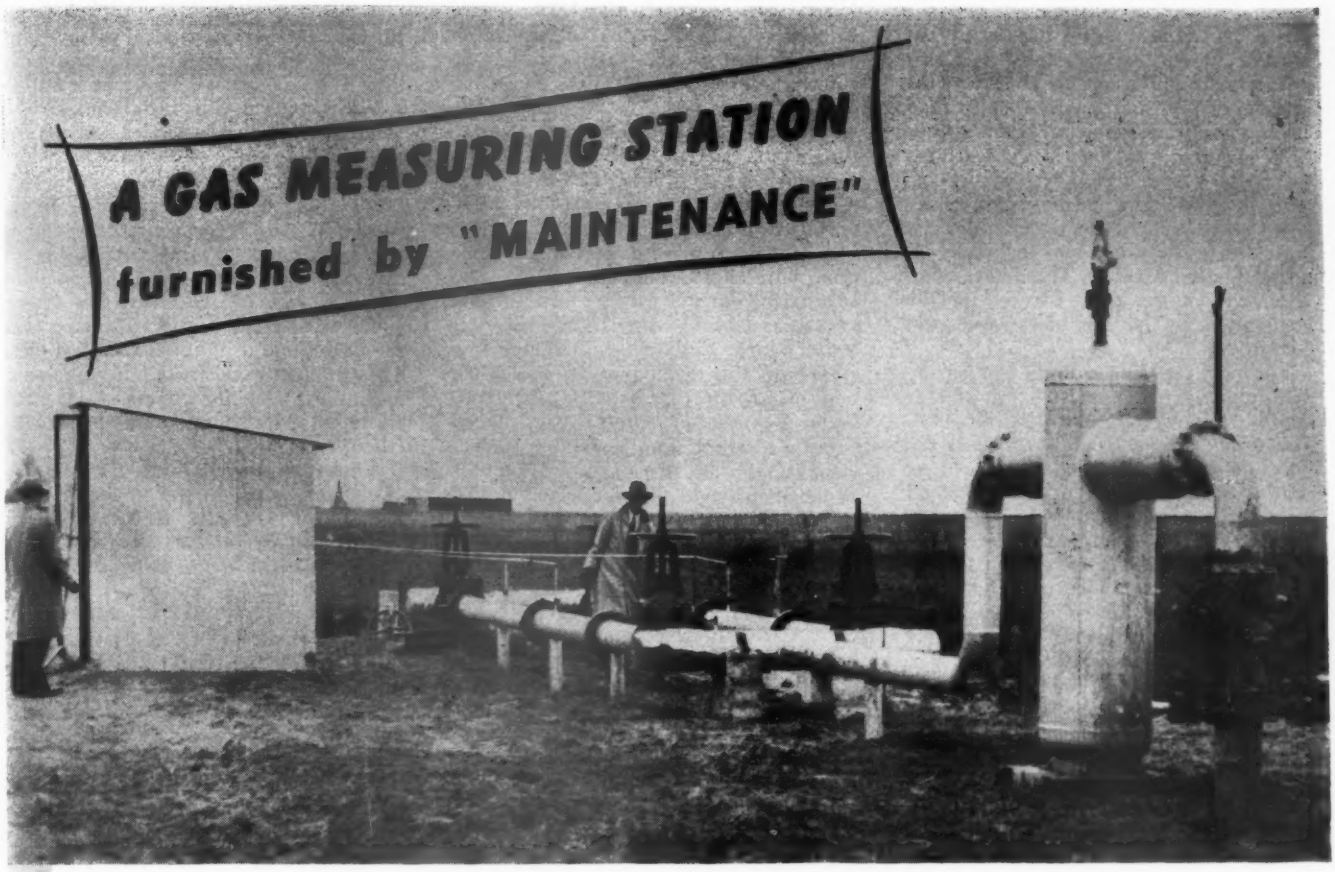
into four general divisions: (1) Characteristics of the soil; (2) voltages or potentials; (3) currents, and (4) miscellaneous. The various instruments and auxiliaries will be discussed along with the measured quantities.

As has been pointed out already, the most useful property of the soil for our present purposes, is its resistivity. In order for electrolytic corrosion to proceed (and there is a very real possibility that *all* corrosion is electrolytic) there must be a medium to conduct the current, and, in general, the more readily the current can flow, the more rapidly the corrosion will proceed. Hence the extreme importance of the conductivity, or its reciprocal, the resistivity, of the soil. This quantity, the resistivity, is defined as the resistance in ohms of a one centimeter cube of the material, measured between parallel faces. It is *not* correct to refer to this as "ohms per cubic centimeter," for this would imply that the total resistance is proportional to the volume of material. Less misleading, but still not technically correct, is the term "ohms per centimeter cube." The correct dimensional unit is "ohm-centimeters." All three will be found in the literature, and all three actually refer to the same unit.

This value may be measured by placing a quantity of the material in a box with parallel conducting faces, the other four sides being of insulating material. If the sides are one centimeter in length, the resistance between the conducting faces gives the resistivity directly, while for other dimensions the correction is easily made. This method is open to several objections. In the first place, it is dificult to be sure that just the resistance due to the material under study is being measured. Second, if direct current is used, polarization will affect the results by introducing additional film resistance. Finally, the trouble of collecting samples, the difficulty of maintaining moisture content at the correct value, and general clumsiness of the method make it unsuitable for field work.

A method that enables us to measure the resistivity of the soil in the field, without disturbing it at all, is much more satisfactory for our purposes. In addition to simplifying the work, it makes it unnecessary to collect samples of every kind of soil, carefully map their extent and location, and then try to piece the whole picture together. What we really need is an average value of the resistivity over a certain range. Four methods are available; we may use either direct or alternating current, and with each we may use either two terminals or four terminals. All four of these combinations are in actual use in corrosion survey work, with several variations of some of them.

The simplest combination is the use of direct current with two terminals. The principle involved is that of measuring the current that will flow through the soil when a fixed voltage is applied to it through two terminals a short distance apart. The voltage is supplied by a small battery, and the current is measured by a milliammeter, calibrated to read directly in ohm-centimeters. As we are not dealing with a small quantity of material confined in a rectangular box, but rather with a semi-infinite conductor, it is not surprising to find that the laws of calculating total resistance are somewhat different from those applying to small objects of finite dimensions, such as bars and wires. It works out that the current passing from one electrode to the other is almost completely independent of the distance between them, under certain conditions. These conditions are: (1) That the distance between the electrodes be large compared to the size of the electrodes themselves (10 to 20 diameters is ample), and (2) that the soil in the immediate vicinity be of fairly uniform resistivity. If the latter condition is not realized, no great damage is done, for the reading will then represent a kind of average of the resistivity. In order to prevent the blocking effect of direct current by polarization referred to above, it is customary to make one of the electrodes (the cathode) of considerably larger area than the other. The Shepard Earth Resistivity Meter, operating on this principle, consists of a pair of canes, in one of which is mounted the meter and two flashlight cells for a battery, together with accessory connections for



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changing the range and for testing the battery. In use the two canes are thrust into the ground about 18 in. apart, the key depressed, and the resistivity read on the meter. The value read corresponds to the average resistivity of the earth between the electrodes. If it is desired to read the resistivity at pipe depth, two holes must be made to that depth (not too close to the pipe) and the canes inserted for the reading. This instrument, although not the most precise for the purpose, is by far the most rapid and convenient.

For more precise readings, and for the determination of the resistivity at greater depths, four electrodes must be used. The usual arrangement is to place the four in a straight line, equally spaced, as shown in Fig. 1. Current is introduced through the two outer electrodes, which may be of any conducting material—stainless steel is quite convenient for the purpose. The two inner electrodes are copper sulphate half-cells, in order to avoid polarization errors. The potential drop across the two inner electrodes is read with a potentiometer or a vacuum tube voltmeter. The resistivity is then given by the expression: $\rho = 2\pi a \, {}^{E}/_{I}$

Where: ρ = resistivity in ohm-cm.; a = distance between electrodes in cm.; E = potential in millivolts, and I = current in milliamperes.

If there is any current flow through the soil due to causes other than the apparatus used, errors will be introduced in the readings. These can be cancelled out by reversing the direction of the current (and necessarily also the potentiometer connections) at each location, and using average values for E and I. The resistivity measured is a rough average down to the depth "a." It is obvious that this method is much slower than the use of the Shepard cane, and requires the transportation of more apparatus.

A still more precise, and at the same time more rapid, method, is the use of alternating current with a four-electrode system as just described. The four electrode Earth Resistivity "Megger" operates on this principle. In operation, four electrodes (all metallic, for there is no polarization effect) are placed along a straight line, as in the preceding system. The two current terminals of the instrument are connected to the outer pair, and the two potential terminals to the inner. The crank of the instrument is then turned, and a value "C" read on the scale. The resistivity is then given by the expression:

$$\rho = 2\pi a C$$

Where C = the scale reading, in ohms, and the other quantities are the same as in the direct current four-electrode method. Turning the crank of the instrument generates direct current, which is passed through the current coil of the meter, and then converted into alternating current by means of a commutator mounted on the same shaft. This current is passed through the soil, and the resultant alternating potential drop picked up by the inner pair of electrodes. This is then fed through another commutator mounted on the same shaft, thereby being converted into direct potential, which is then fed to the potential coil of the meter. The combined action of the two coils causes the needle to come to rest at a point corresponding to the ratio E/I, so that actually this method is equivalent to the preceding one, except that reversal to avoid the effect of stray currents is unnecessary, and the effects of polarization are avoided. Although this system is faster and less subject to error than the preceding, it requires a special piece of equipment not used in other phases of the survey, while the direct current method makes use of instruments needed for other work.

A fourth variation is the use of an instrument similar to the Shepard Cane, in that only two electrodes are employed, but using alternating current instead of direct. There seems to be very little advantage to be gained, except in very low resistivity soils, where polarization may be severe enough to affect readings.

Some effort has been made to measure soil resistivity by means of radio frequency absorption, but as yet no instrument light and compact enough for practical field use has emerged from these efforts so far as the writer knows.

It would seem that chemical analysis of the soil would be useful information to obtain in a corrosion survey. Here, however, is an exemplification of the basic difference between this problem and other corrosion problems. In almost

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any other instance of corrosion, an analysis of the corroding medium would be made as a matter of course. In the case of soil corrosion, however, such an analysis is out of the question, for literally hundreds of samples would be required per mile of line in many cases. Even if this tremendous laboratory job were executed, the interpretation and correlation of the results would be an impossibly complex task. Rarely does a peculiar condition arise that justifies a chemical analysis of the environment of some short section of a line.

There is somewhat higher justification for a study of the hydrogen ion concentration, usually expressed as pH, of the soils along a line. The correlation between pH and corrosivity does not seem to be as high as that between resistivity and corrosivity, however, and pending the development of more rapid and simple means of pH determination, it is not likely that the measurement of this factor will form an important part of many corrosion surveys.

Information must be collected concerning the physical characteristics of the soils, as has been mentioned. This data usually appears as notes and comments concerning rocky sections, heavy clays, sand, etc., rather than as any set of actual measurements. Sometimes it is not collected with the corrosion survey proper, but is added thereto at a later date from another source.

A very important quantity to be determined is that of voltage or potential. We have already seen how it is involved in one method of determination of soil resistivity. In addition, probably the most useful single function of corrosive activity on an existing line is the pipe-to-soil potential. This is usually determined by measuring with a suitable instrument the voltage existing between the metal of the pipe itself and a copper sulphate electrode placed in contact with the soil nearby. Just where this electrode should be placed is the subject of a great deal of discussion. If it is placed very close to the pipe—almost in contact—we get a more nearly true voltage, but in order to place it there we must remove the soil and so tear up the structure we are trying to investigate. We also run the risk of missing something happening perhaps a foot or two away. If we place the electrode immediately over the pipe, at the surface of the ground, we are in error by an unknown amount due to the voltage drop through the soil to the surface of the pipe. Besides this, we get a sort of average potential relative to all the pipe in the immediate neighborhood. But, since we cannot take readings all over the pipe, and since it is so much easier and quicker to set our electrode at the surface, this is the practice generally followed.

In measuring voltages of this kind, it is necessary to use a potentiometer or a vacuum tube voltmeter, in either of which instruments the potential being measured is balanced against an equal voltage from the instrument, so that at the time the reading is taken, no current is flowing in the external circuit. This is most important, for the resistance of the external circuit is a highly variable quantity, and to attempt to correct readings for the losses therein would be hopeless. Nor are these errors small by any means. An instance was encountered where two points on a pipe less than 200 ft. apart both showed pipe-to-soil potentials of 650 millivolts with the potentiometer. One of these points read 440 millivolts with a voltmeter (clay), whereas at the other one the needle barely moved off of zero (sand).

It is also necessary to be able to measure the potential difference between two points on the surface of the earth. For this two copper sulphate electrodes are used, and the problem differs from the preceding one only in the size of the voltage measured. Such potential differences will range from 1 or 2 millivolts up to 50 or 100. If there are currents present due to electrical equipment, the range will be still higher. Occasionally natural differences are found as high as 400 millivolts in a distance of 100 ft., due to no other cause than a corroding pipe line, but such magnitudes are rare.

Whenever there are two separate underground structures, it may be useful to measure the potential between them. They may be two pipe lines, or two sections of a line separated by an insulated joint, or a pipe line and some other structure. The resistance of the external circuit, except in the case of extremely well coated lines, will be much lower in this case than in either of the two preceding. The needle of the galvanometer will be

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much more sensitive, and it may even be necessary to substitute a galvanometer system having a lower resistance.

A most important quantity to be observed is the value of the current flowing *along* the pipe line. By measuring this at intervals, it is possible to locate points of current gain (cathodes) and current loss (corroding anodes). As it is impossible to open the circuit and insert an ammeter, it is necessary to determine this quantity by indirect means. This is done by measuring with the potentiometer the voltage drop in a known length of pipe (100 ft. is a convenient value) and computing the current from the resistance of the pipe. The determination of this very low voltage with precision places the severest demands on the instrument. The value may be only a few tenths of a millivolt, and the external circuit resistance is quite low, so the needle is very sensitive. It is still necessary, however, to use a potentiometer rather than a voltmeter, for the leads and pipe contacts together have a fairly large and usually quite unknown resistance.

The writer encountered a peculiar situation a few months ago when engaged in this type of survey. A section of 12-in. line paralleled a number of 66,000-volt and 12,000-volt circuits, not far from a large power plant. Undoubtedly a considerable part of the return current from these lines was flowing along the pipe line. There was known to be an insulating joint in the line, but the records of its location were incorrect, and its position was unknown. In order to locate it, current readings were taken on successive 100-ft. sections of the pipe, the theory being that either there would be an appreciable voltage across the joint, or at least the resistance would be so much greater than the plain pipe that the behavior of the galvanometer needle would disclose the presence of the joint. The third attempt did, in fact, span the joint, but the behavior of the needle was not exactly what had been expected. There was, it appeared, an alternating (60 cycle) voltage across the joint; in fact, the two flanges and their insulating gasket, acting as a condenser, were probably carrying some alternating current. This alternating current, passing through the galvanometer, made the needle vibrate so that it became a hazy blur, about four times its true width. As there was some question as to what this might do to the instrument, the circuit was closed only long enough to obtain a rough balance, indicating in addition to the a. c., a d. c. component of about 35 millivolts. The contacts were then moved closer together, until the exact location of the joint was determined, and it was then excavated for inspection, according to the original intention.

Not all the currents encountered in corrosion work can be measured with a potentiometer. We have already mentioned the use of a millammeter in the four-electrode determination of soil resistivity. There are also the protective currents involved in any scheme of cathodic protection, either with rectifiers and generators, or with galvanic anodes. As these currents flow through wires and cables, it is possible to make provision at the time of installation for their measurement with conventional ammeters of the proper range.

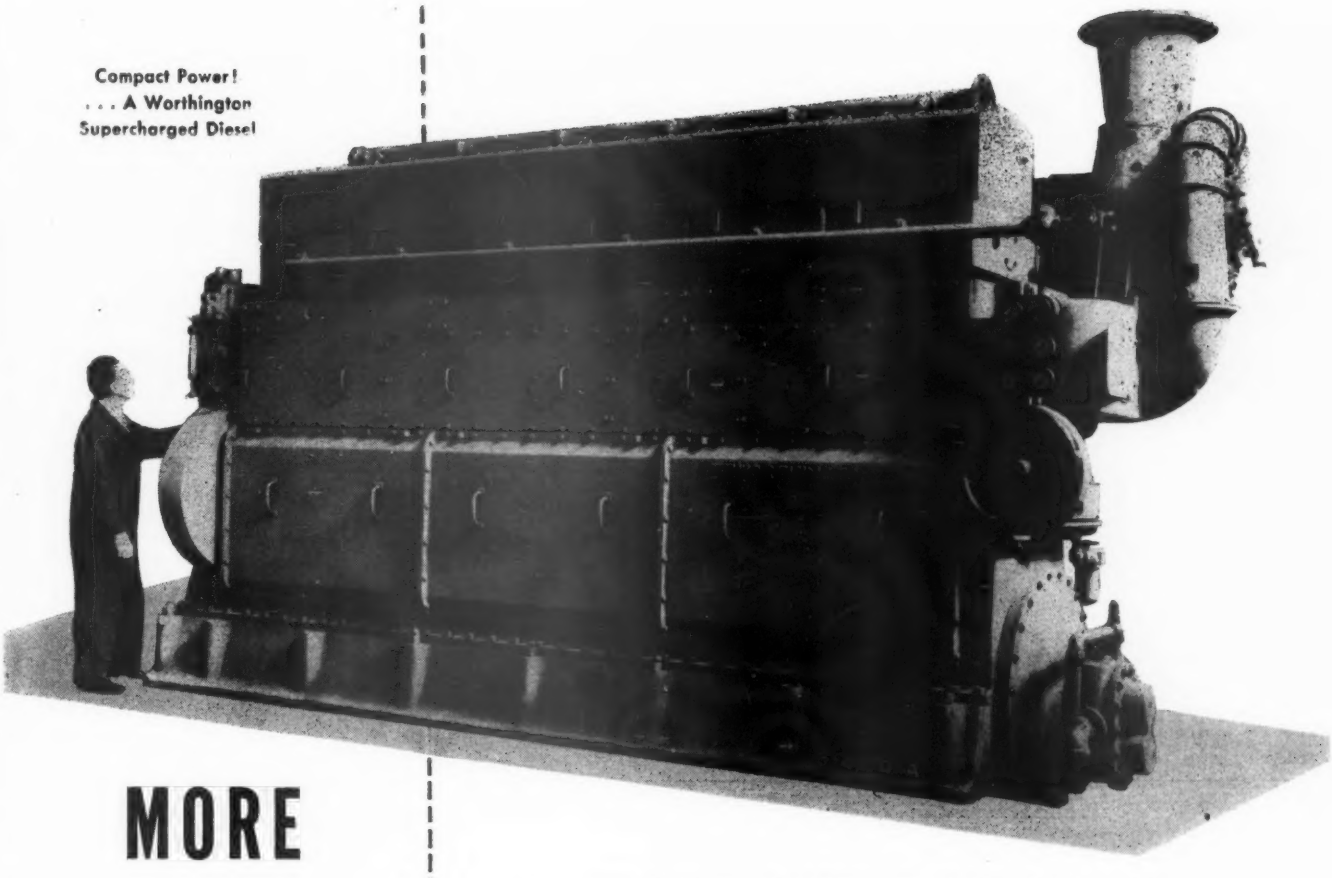
One other current measurement is of interest, and that is the current flowing through the soil itself. This measurement is subject to a variety of complicating factors, largely due to the irregular distribution of earth current because of the variable resistance of different paths through different strata, and is thus a difficult quantity to determine. Much experimental work has been done on this problem, but it cannot be said that there is available a method that is sufficiently rapid and simple to enable the survey to be made with an adequate degree of completeness.

The copper sulphate electrode has been mentioned in its several uses. It should always be used where a potential reading is to be taken relative to the earth, simply because any type of contact with the earth introduces some kind of voltage error at the surface of contact, and both theoretical and experimental considerations indicate that this particular contact is less variable, less subject to error, than any other simple, easily reproduced contact. The principle is this: From the instrument circuit a conductor is run, which may be of any conducting material, but is usually a copper wire. This conductor makes a dry connection with the terminal, and from that point the metal must be copper. Some area of copper is in contact with a saturated solution of copper sulphate, and this solution itself is in contact with the ground. The area of contact between the copper and the solution must be large enough to insure that the largest current passing will be below the polarization level. The area of solution in contact with the ground is important only in that it affects the total circuit resistance. It should be noted that the current at the time of reading is zero, but that in the process of balancing the potentiometer some current flows, and it is this current—the value corresponding to maximum unbalance—that determines the necessary area of copper to copper sulphate solution contact. The usual form of electrode is a tube of insulating material enclosing a copper tube filled with solution. This is closed at the top by a copper plug including a binding post, and at the bottom by a wooden plug that allows the contact between solution and soil. In dry weather it is frequently necessary to pour a little water in the hole in order to increase the conductivity in the immediate neighborhood of the electrode. It is possible to take a reading on top of a solid dry pavement by first placing thereon a shovelful of mud, and inserting the electrode in the mud.

In order to take soil-to-soil potentials along the line, and to take the potential drops for determining line current, at least one long lead is required. It is convenient to combine this with the necessary means for measuring distances. The writer uses a lead 120 ft. long, with two brass rings on the wire 100 ft. apart, and smaller rings at every 10 ft. Measuring thus from points not at the end of the wire gives 10 ft. of leeway to find a good place to set the instrument, and also makes it possible to repair or replace the terminals without affecting the length of the marked portion. These terminals take terriffic punishment, being dragged along the ground, and having to be put on and taken off 200 to 300 times a day. Ordinary copper terminals will hammer out of shape in a few weeks, but monel metal or stainless steel has been found to be very satisfactory.

Reference has already been made several times to establishing electrical contact with the pipe, but so far no means has been described for doing this. There are three methods in common use. One is the use of a clamp that encircles the pipe and carries a binding post for wire connection and a pointed contact screw, capable of piercing coating, scale, and rust, for contacting the metal of the pipe. The use of such a clamp requires excavating a hole below the bottom of the pipe and large enough to work in while installing the clamp. Another method makes use of a contact bar with a binding post at the top, and a stellite tip on the bottom. Some forms carry a removable point, such as a quarter-inch drill, instead of the stellite tip. Successful use of this bar requires a certain amount of skill and some precautions. A hole is punched with a steel bar, larger in diameter than the contact bar, down to the pipe. It is important that this hole be centered accurately, for it is almost impossible to make good contact off center. The contact bar is then held firmly in both hands, and the pipe stabbed with it. When it hits the pipe, the hands should be permitted to slide a little along the bar, and a firm uniform pressure then maintained. At least three different contacts and readings should be made at each location to be sure of getting the correct value. The tiniest piece of rust, a single grain of sand, or almost anything can either insulate the contact, or what is worse, introduce a false voltage of its own to vitiate the readings. A third and more satisfactory type of contact can be made by attaching a wire directly to the pipe, by welding, brazing, or soldering. This requires less excavation than the use of clamps, but more than the contact bars. It is possible to patch the damaged coating, however, which is not the case when contact bars are used. If soldering is the means used, it is not necessary to carry any heavy equipment along, and the survey party, or two men working ahead, can easily attend to it. If the wires are installed near roads and fences, the free end of the wire can be taped and attached to a fence post, just below the ground, where it will not be noticed by passers-by, but can readily be found for later investigation.

● **Records, notes, and reports.** In order to make effective use of the survey data, the readings of various kinds must be located accurately along the line. This location must be the same as that used in reporting leaks and repair work, and it must be of such nature that it can be re-



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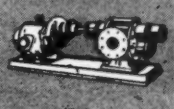

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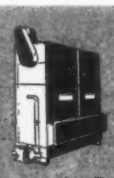

Evaporative Type Engine Water Cooler

produced at any time, so that future surveys will correlate. For this reason it is not sufficient to start at a known point and simply measure successive distances along the line. The accumulated errors would be too great, and there would not be any good way of going back to a specific location. Consequently, a good alignment map of the line must be had, or at the very least, a set of survey notes. Usually the stations used in a corrosion survey will be those established by the inventory survey, made shortly after a new line is constructed, rather than the stations used for construction itself. If the long lead as described above is used, errors will accumulate and must be corrected from time to time. Usually, if care is taken to make corrections at every identifiable fence, road, or other marked point, the error will be quite small and of no particular consequence. The problem is simple if there is a telephone line along the right-of-way, as is frequently the case, for the poles are usually numbered conspicuously, and are used by linewalkers, connection foremen, and others in giving location.

Foremen in charge of leak repairs must be instructed to give locations accurately; if no mile post or marked pole is near enough, then the distance should be measured to a fence, and enough description added to insure the correct identification of the fence. Too often the location of a leak is given as "half mile south of gravel road," or some equally vague description. If this were "thirteen feet north of a fence half a mile south of the gravel road from A to B," then there would be no difficulty in fixing its precise position.

It is also necessary to gather information, to be incorporated in the graphic account of the survey, from sources other than the field. Included in this category is such information as the dates of construction, type and weight of pipe laid, whether new or second-hand when laid, kind and amount of coating applied originally, and even the kind of weather prevailing at the time of construction.

If the line in question occupies the same right-of-way with another line, it is also quite useful to obtain, as far as possible, the experience of the other operator, making use of the principle that there is no better evidence of the corrosive nature of a soil than a piece of corroded pipe. Even if there is no immediately adjacent line, it will frequently be possible to obtain some information on the general behavior of buried steel and iron in the localities in question.

If any reconditioning, relaying, or repairing of line is necessary, the depth to which pitting has taken place by all means should be obtained. It will not be practicable, of course, to measure and record every pit and its location, so some definite procedure must be followed to get a reliable record. For locations showing severe local action, the pipe may be marked off in sections of perhaps 10 ft. in length, and the average of the three deepest pits taken—or perhaps the depth of the one deepest pit, with some descriptive data on the general extent of pitting. For a general survey along a whole section of line, the recording of the deepest pit in each 100-ft. section, with notes as to general severity, should prove sufficient. Data of this nature must be evaluated in connection with the length of time the exposure has existed, and the kind and amount of coating applied.

There should also be recorded as complete a record of corrosion leaks as it is possible to obtain. The importance of obtaining accurate locations for these leaks cannot be over-emphasized. Naturally, there will be many cases in which the records of older lines will be very incomplete, both as to the locations and even the number of leaks, but a serious effort should be made to get as much of this information as possible, even though much of it must be obtained by talking to old-timers who worked on the lines.

Summarizing briefly, the data that is to be plotted on the survey charts will include all or part of the following: (1) Pipe-to-soil potentials; (2) line currents; (3) soil resistivity; (4) record of pit-depths (on lines that have been inspected); (5) record of leaks; (6) records of repairs and maintenance; (7) an alignment map for correlating locations; (8) a profile of the line, and (9) crossing and paralleling pipelines and other relevant structures.

Normal pipe-to-soil potential, as measured to a copper sulphate electrode, is somewhere in the neighborhood of 550 millivolts, the soil being positive with respect to the pipe. When there are no voltages present except those generated by interaction between the pipe and the soil, this value will vary perhaps 200 millivolts either way. Consequently, if we are not going to apply any type of cathodic protection, and if we were not going to encounter any stray current interference, we would need a scale for our chart running from, say 300 millivolts to 800. Actually we shall need one from about zero to perhaps 3000 (3 volts). The direction in which this scale is drawn, unfortunately, has not been standardized. Some plot the potential down from zero, some up. As the potential variation along the pipe itself is comparatively small, and thus most of the variation is in the soil, it seems that we should refer to soil-to-pipe potential, rather than pipe-to-soil, and plot it as a positive (upward) potential. Actually, this is a trivial matter, and never leads to more than momentary confusion when inspecting the records of some other corrosion engineer.

The vertical scale, then, must include 3000 millivolts. It will be found that, for any reasonable size of chart, this scale is too compressed to show significant potential differences on unprotected pipe. Consequently, it will usually be desirable to use a different scale when considering unprotected pipe and that under cathodic protection. A very important consideration is the proper relation between the vertical scale (potential) and the horizontal scale (distance). If the vertical scale is too compressed, significant peaks will fail to show up. If it is too extended, the plot as a whole will be so irregular that it will be difficult to select the really important variations. There seems to be room for some research and development work on this important matter.

The value of the line currents found will have to be plotted also, and can usually be superimposed on the same graph without confusion, and with a definite saving in time and space. These values will be measured about every 1000 ft., and will of course have magnitude and direction. This means that we will need a center zero scale, or must adopt a device to achieve the same result. The really important thing about line currents is not the magnitude of the current at any one point, but the magnitude of the *change* in value between successive points, for this indicates either current gain or current loss. If it is current gain, then there is no damage being done (except the collection of current that must be dissipated somewhere). If, on the other hand, it is current loss, then there is active corrosion, and that is exactly what we are looking for.

One way to emphasize this important feature is as follows. At each point where current was measured, plot the value of current read. If the direction of current at two successive points is the same, connect these points by a straight line carrying an arrow pointing in the direction of current flow. An arrow pointing *down* a line will then indicate current loss, and the slope of the line will be an indication of the rate of loss averaged over the section. If the flow at two points is in opposite directions, then instead of a line connecting the two, a pair of lines having equal slopes should be drawn, intersecting on the base or zero line, and arrows shown as before. Again an arrow pointing down indicates current loss, and the slope indicates the rate.

The plotting of soil resistivity offers its share of problems. In the first place, we would probably be better off if we considered its reciprocal, conductivity. For a difference in resistivity between two soils reading 10,000 ohm-cm. and 9,000 ohm-cm., for example, is not very important, while the difference between 1,000 ohm-cm. and 200 ohm-cm. is quite important. If we expressed these as conductivity, we should have in the first case 100 and 111 micromhos per cm., and in the second, 1000 and 5000 micromhos per cm. Even where the conventional resistivity units are employed, it is very common practice to invert the scale, so that the peaks will be the danger points, rather than the valleys. It is also necesary to use a variable scale—sometimes logarithmic, and sometimes a modification of logarithmic, so as to emphasize the differences between the lower resistivities to somewhere their true importance.

A chart may also be incorporated to show the depths of corrosion pits, as described above. By using a different symbol, this may be shown on the same scale as the line currents and pipe-to-soil potentials. Ordinarily, this record will only be available on such sections of the line as have been reconditioned.

The leak and maintenance records may be kept on the same charts, with location

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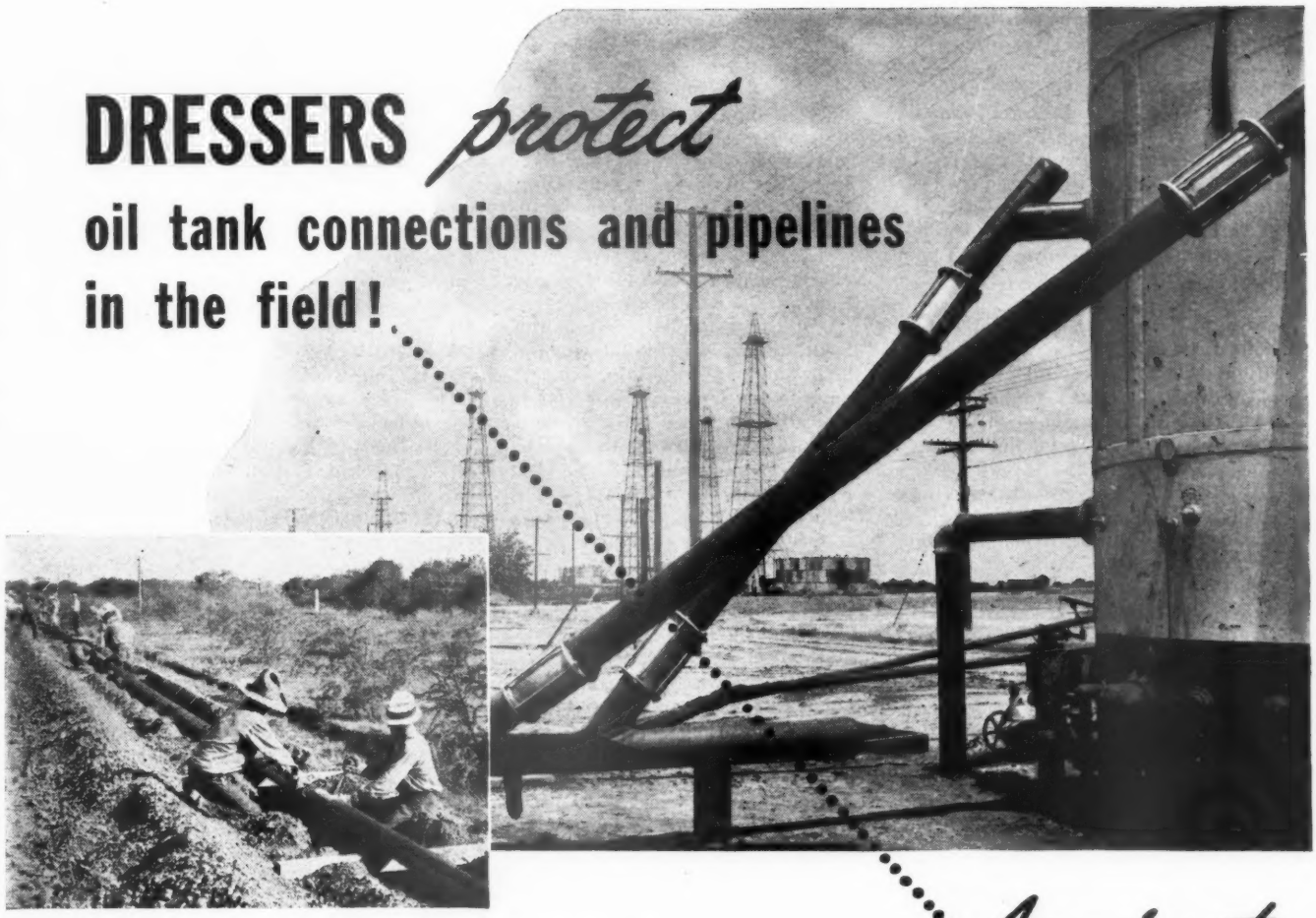

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shown by their position and time of occurrence either by vertical position or by notes. The type of repair made may be indicated by suitable symbols.

The alignment map and profile should appear at the same horizontal scale so that the location of everything may be seen at a glance. On the alignment map there will appear all the information about crossing and paralleling pipe lines, electric transmission lines, railroads, and other pertinent data.

All this data may be recorded on a plat whose vertical dimension is 11½ in. as shown in Fig. 2. The various scales, reading from top to bottom, with their vertical dimensions, are as follows:

(1) Station numbers—½ in.
(2) Record, leaks and maintenance (20 years)—2 in.
(3) Recommendations and corrosivity estimate—½ in.
(4) Soil resistivity 10,000 to 100 ohm-cm.—1½ in.
(5) Pipe-to-soil potential, line current, and pit depths—3½ in.
(6) Alignment map—1½ in.
(7) Notes on topsoil and subsoil—½ in.
(8) Profile—1½ in.

The horizontal scale used with this particular combination is 1000 ft. to 1 in. It is doubtful whether this scale could be changed very much without some trouble at one or more points, necessitating changes in the vertical scales.

A chart using the above scales (or any other combination) may be made either in the form of a continuous strip map, covering several miles of line, or in separate sheets. The former is most economical, both of time and paper, but the latter is more convenient for most uses. It is easier to post new information on, and much easier to handle, but it is a little difficult to get a general view of conditions along a whole line section at a glance.

There are several types of special charts the corrosion engineer needs from time to time. One of these is the resistivity plat of a limited area, to aid in the location of a suitable site for an anode bed. This is drawn in a manner analogous to the construction of a contour map. Readings are taken of the soil resistivity at a certain depth (usually 8 ft.) at suitably distributed points—100-ft. intervals in both directions will usually suffice. Then a series of lines are drawn connecting points of equal resistivity, obtaining values between the actual readings by interpolation. It is usually a good plan to make the first rough draft of such a plat in the field, so that additional readings may be obtained at closer intervals where the picture is confused. From such a plat it is possible to select the best locations for the anodes, or to determine a trend leading to a nearby more suitable site.

A cumulative record of corrosion leaks on a given section of line is useful in making predictions as to the expected number of leaks in future years if the conditions are not changed; that is, if there is no reconditioning or installation of protective devices. The mathematical laws of probability tell us that, for a very large exposure (one in which the total number of events, i.e. leaks, would be large) such a graph, if plotted on logarithmic paper, should be a straight line. This would require the use of a logarithmic time scale, and there is not any very good way of deciding the starting point. For this and various other reasons, chiefly convenience, it is just as well to use semi-logarithmic paper, with a uniform time scale and a logarithmic scale for the number of leaks. Such a graph is not really valid insofar as predictions are concerned, until the number of leaks has reached something like 40 or 50; by that time something would certainly have been done about the condition. However, some idea of the trend can be had on numbers as small as eight or ten, but everyone using or seeing the graph should be cautioned not to place too much reliance on it.

● **Procedure for a typical survey.** Perhaps a brief description of the actual procedure followed in making a specific survey may be useful. Let us consider a survey made along a single pipe line, several years old, not under cathodic protection, and not previously surveyed. We are going to collect data on pipe-to-soil potential, line currents, and soil resistivity (at the surface). Our first step will be to obtain alignment maps showing the stationing as established by the inventory survey. These maps should be compared

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with the notes, and any pertinent information added. Then investigation should be made about roads in and out of the area, since this will not appear on the narrow strip with which the alignment concerns itself. The map should then be put in such shape as to enable its being carried in a pocket, which may require some ingenuity in cutting and folding. This is a problem not to be taken lightly, though; one of the severest shortages on a survey party is shortage of hands to carry things in.

In advance of the actual survey, wires should be installed at convenient locations, averaging about half a mile apart. As many of these as possible should be put on roads, trails, or other accessible points. Seldom will such points occur close enough together, so many will have to be in remote places. These should be put in fence lines if possible, and in every case, careful notes should be made of their locations.

Four men comprise just about the minimum party; five is better. Four men will have the following equipment to carry and use: (1) The party chief; notebook, maps or earlier notes, and the Shepard canes; (2) instrument man; potentiometer, one copper sulphate electrode with 15-ft. lead attached, and one end of the 120-ft. lead; (3) electrode man; one copper sulphate electrode, one end of the 120-ft. lead, and drinking water; (4) utility man; locating bar, contact bars, and water can (for contacts).

The survey gets under way by taking a pipe-to-soil reading at one of the wires; connecting one terminal of the potentiometer to the wire and the other to an electrode placed directly over the pipe at an even station. The station is recorded, and the potential reading just described. The instrument is then moved 100 ft. past the electrode position, the second electrode placed directly over the pipe at this station, and the potential difference between the two soil contacts measured. This value, added algebraically to the reading on the wire, will give the pipe-to-soil potential at the second station. The second electrode is then moved 100 ft. past the instrument, and the process repeated. It will be seen that the instrument moves 200 ft. each time, as does the second electrode. This requires careful attention to the polarity of the various potentials—reading and recording.

The party chief will always be somewhere near the instrument, in order to record the readings as they are made. As he moves up his 200 ft., he takes resistivity readings from time to time—possibly eight or ten per 100 ft.—and mentally records the highest and lowest readings in each 100 ft. When he reaches the end of the second station, he records these values while the instrument is being connected and the potential read. This work is not arduous, but it does require a considerable amount of concentration, and makes it difficult for him to give the proper amount of attention to a general look around for anything that might be pertinent. If a fifth man is available for the party, he should be given the task of determining the resistivity and reporting it at 200-ft. intervals. This leaves the party chief with the job of recording the data, and gives him enough freedom of mind to look out for the general work of the party.

The work proceeds in this fashion until a point is reached within 100 ft. of a wire. The reading is taken on this point just as usual, and is then followed by a direct reading of this potential with respect to the wire. This value will differ from the derived value by an amount equal to the net potential drop in the pipe between the two points, plus the accumulated errors of observation. If the discrepancy is not too large, it should be distributed equally among the several readings; this work is done later in the office. The distribution, instead of being strictly equal, may be modified to throw the larger part of the correction to readings taken on higher scales of the instrument; but the practice in this respect is highly variable.

Interspersed with these readings are the line current determinations, by taking the potential drop in 100 ft. of pipe. These are taken at 1000-ft. intervals ordinarily, but additional readings should be interpolated when very abrupt changes are found. This means a certain amount of backtracking, but with present facilities this seems unavoidable.

All of the above data must be recorded in a field book. The kind ordinarily used for level notes has been found most suitable, using the following form.

Sta.	Resis. ohm-cm.	L. C. mv.	S/S mv.	P/S mv.	P/S corr.
1380	500 1100	N 0.12		(661)	661
1381	650 2100		—11.0	650.0	
1382	600 6000		+9.0	659.0	
x	x	x	x	x	x
1403	9000 15000		—32.0	(653) 643.0	

The potential values in parentheses represent values read directly from the wires; the 10-millivolt discrepancy between the 643 millivolts derived by adding successive soil-to-soil potentials algebraically to the original 661 millivolts and the 653 read directly at station 1403 must be distributed over the 23 stations intervening; the corrected values will be entered in the last column, to the nearest whole millivolt.

● **Some possible future developments.** I should like now to take a look at some of the possible future developments in the field of corrosion surveys. The item in which we are actually interested is the existent corrosion rate; this is, in the amount of current leaving the pipe itself, or the *density* of such current. Any method that gives us only values at 100 ft. intervals is clearly an incomplete method, for corrosion in soil is typically a highly local action. If the anode and cathode are close enough together, the corrosion may be quite severe, and yet cause almost no electrical effect 2 or 3 ft. away. There are, in theory at least, three methods of measuring this pipe-to-soil current. One is the measurement of pipe-to-soil potential, as has been described; another is the measurement of the current flow in the line, and from the changes in this current the determination of current gain or loss; the third is the direct measurement of the current in the soil, radial to the pipe.

In the use of pipe-to-soil potential, the greatest weakness is the danger of passing over completely some very critical points, simply because we take the potential every 100 ft. Closer spacing by the present methods would enormously increase the time consumed, and hence the cost of the survey. What is needed is an instrument for recording the potential all along the line in a continuous record. Such an instrument would require a self-balancing recording potentiometer; a chart reading in distance instead of time; a large-area electrode contacting the surface of the ground; and a connecting wire on a reel. The instrument itself could be set up and connected to the pipe by a soldered wire. Then the electrode could be moved along the ground directly above the pipe, unreeling a wire as it goes. This process could be continued for a thousand feet, or half a mile, until another wire is reached. At this point the recorder is disconnected, the free end of the lead connected to the second wire, and the total voltage drop in the pipe determined. There are many details to be worked out in the design of the device, but none seems insuperable.

A still more radical scheme may be based on the determination of line currents. We need here a potentiometer with a sensitivity 100 times as great as those now in use. (Such instruments exist). Furthermore, it must be small, self-balancing, recording, battery-powered, and shock-proof. With such a sensitivity the current in a pipe could be determined by reading the drop in a ½-ft. length. What is proposed is to put such an instrument *inside* the pipe, and drive it along in the same manner as a scraper. The chart, or more probably film, could be driven by a gear motion, so that its travel would be proportional to the length of pipe. As this would probably be very inaccurate, it might be necessary to incorporate a clock, to indicate time at fixed intervals. The passage of the scraper by certain points on the line could be timed, and the record adjusted to agree. Or a recording clinometer could be incorporated into the apparatus, and the record correlated with the profile of the line. Here again there are many details to be worked out, and some of them might be insuperable.

It is also possible that line currents, or perhaps even the true *current density leaving the pipe surface*, might be measured by apparatus on top of the ground. It is almost certainly true that these phenomena produce some effect at that disance, and if the effect is there, it should be possible to detect it. If it can be detected, it can be measured. It takes a brave man, or a rash one, to label any device impossible or impracticable, after some of the things we have all seen in the last few years. ★★★

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Multi-stage centrifugal compressor applications*

By T. R. FOSTER, *Manager, Centrifugal Compressor Sales, Clark Bros. Company, Inc.*

IN RECENT years there have been large capacity increases in gas and air compression requirements for the oil industry and the chemical process industry.

New processes have been introduced that likewise require larger capacity compression equipment. Consideration of centrifugal compressors has followed as a natural outgrowth of this higher capacity trend. Centrifugal compressors have their greatest economic significance on high capacity applications.

In the past, high capacity centrifugals were synonymous with high volume as most centrifugal blower applications operated at discharge pressures below 50 lb. In the centrifugal compressor field, high capacity may imply higher weight flows due to high gravity or higher pressure with its attendant lower relative volume.

High pressure centrifugal compressors will ofttimes be employed on smaller inlet volume applications than has heretofore been economically feasible in centrifugal blower practice as the shaft horsepower will be high enough for commercial centrifugal application.

The term compressor, in this instance, is used to signify a machine of radial design (Fig. 1) incorporating two or more shrouded type impellers in series discharging gas or air at pressures in the range of 50 to 500 psi.

The tabular presentation (Fig. 2) covers a so-called line of such compressors, covering a range of 2000 to 60,000 cfm inlet volume and maximum discharge pressures from 110 psi to 300 psi in semi-steel. An additional number 1½, 13½-in. diam impeller compressor permits us to accommodate lower volumes and higher discharge pressures. The smaller size machines are available with steel cases, which also permits higher discharge pressures.

Since these machines are not intended for duties of 200,000 to 300,000 cfm inlet volume, which might be more economically served by an axial flow type blower, they may be said to have an economic upper limit of capacity of 120,000 cfm and 22,000 hp. Horsepowers of this magnitude are accommodated by utilizing the drive-through principle. (Fig. 3).

The lower limits of capacity will have to be resolved more often, and since the compression through the compressor results in a reduction in volume, the exit volume is the limiting factor.

Five hundred cfm exit volume and 500 hp per case, or stage of compression, are round numbers that may be used as a yard stick in determining whether a non-refrigerating duty warrants a centrifugal compression investigation. Fifteen hundred cfm minimum inlet volume may be considered as a similar yard stick.

A few applications employing direct steam turbine drives exhausting live steam to process may prove economically feasible down to 300 hp, but most commercial applications may be expected to fall in the 500 hp and higher capacity range.

Utility and driver costs vary to the extent that it is an impossibility to make factual statements regarding gas or air compression duties that might profitably be served by centrifugals.

In general, large capacity centrifugal air compressors find their greatest usage where fuel cost is low. This is true in the case of blast furnace blowers and fluid cat-cracking units. On the other hand, many municipal and manufactured gas duties have been and are being accommodated by centrifugals.

Centrifugals are standard equipment in the steel industry for many applications such as: blowing of blast furnaces, Bessemer convertors, cupolas, and coke oven exhausters and/or boosters.

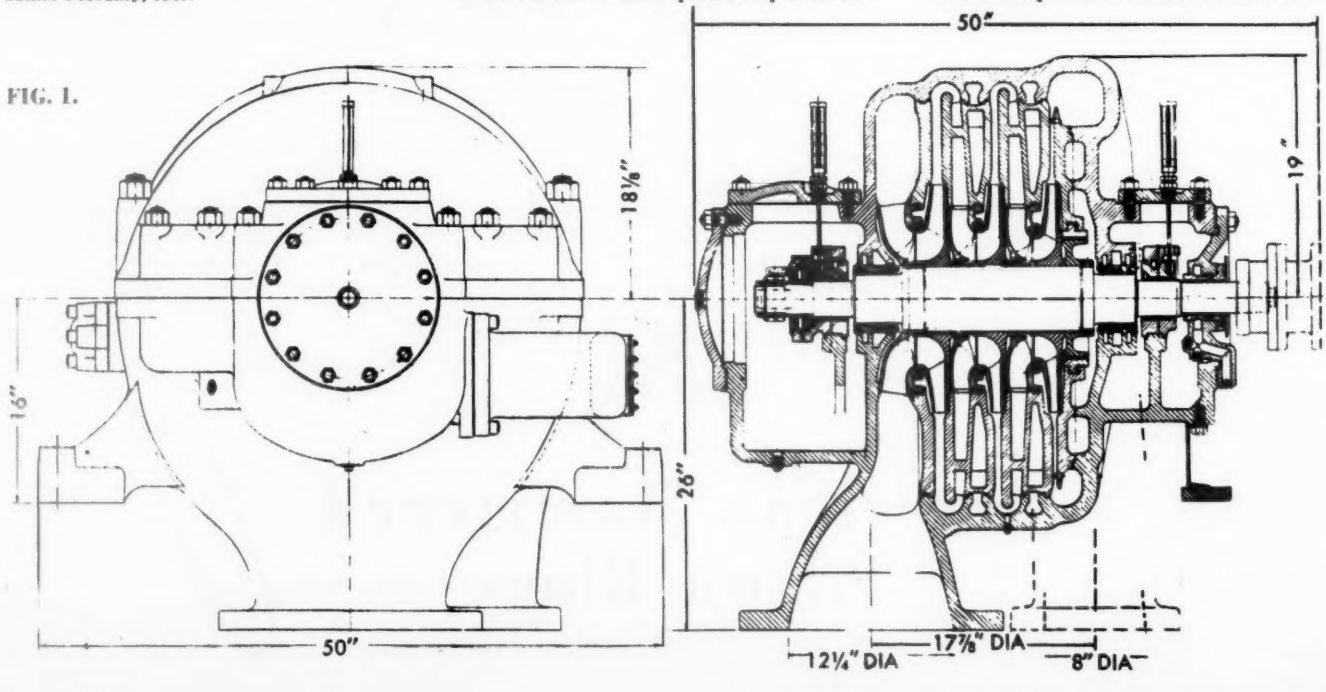
For refrigeration industry applications in the range of 200 hp and upwards the centrifugal compressor is rapidly becoming the standard rather than the alternate type of equipment. A very high numerical proportion of multi-stage centrifugal compressors operating in the United States are employed on refrigeration cycles. The first units installed were in the capacity range of 50 hp to 200 hp per unit. They were not sold as refrigeration units in competition with current competitive machinery but as part of a system in which the buyer was interested in temperature and humidity guarantees rather than cost of machinery components.

Many of the refrigeration units in industries requiring steam for heating purposes employ back pressure turbines exhausting steam for process. Approximately 40 per cent of the centrifugal refrigeration compressors in use utilize steam turbine drivers of different types.

Some 60 per cent utilize electric mo-

*Presented at California Natural Gasoline Association meeting December 5, 1946. Revised by author February, 1947.

FIG. 1.



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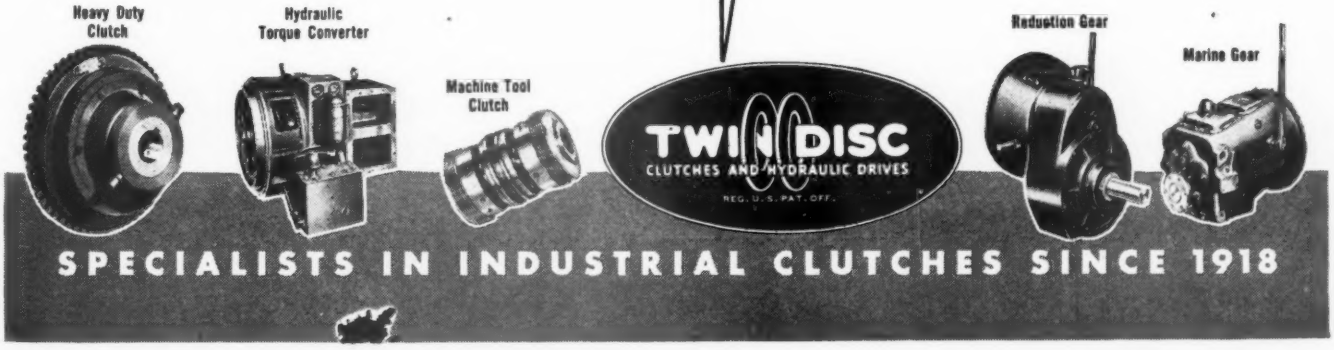


MULTI-STAGE CENTRIFUGAL COMPRESSORS—Standard Sizes

MODEL	NO. 2 COMPRESSOR				NO. 3 COMPRESSOR			NO. 4 COMPRESSOR			NO. 5 COMPR	
STAGES	3	4	5	6	3	4	5	3	4	5	3	4
CAPACITY—CFM—Approx. Maximum	7000	7000	7600	6000	18000	18000	14000	32000	32000	25000	60000	60000
CAPACITY—CFM—Approx. Minimum	2000	2000	2000	1700	6000	6000	4500	12000	12000	9500	24000	24000
TOTAL WEIGHT—Lb	7400	7950	8500	9050	13400	15000	16600	23500	27000	30300	48000	55000
NORMAL SPEED—RPM	9800	9800	9800	8300	7350	7350	5700	5500	5500	4300	4150	4150
SUCTION OPENING—Dia. In.			12			20			30			36
DISCHARGE OPENING—Dia. In.			8			14			20			24
IMPELLER—Dia. In.			18			24			32			42
INTAKE PRESS—PSIG			150			100			80			60
DISCHARGE PRESS—PSIG			300			200			150			110
MAX. SHAFT HORSE POWER			7000			10000			15000			22000

FIG. 2.

tors through speed increasing gears.

Refrigeration units that operate on summer air conditioning are quite often driven by the steam that is available for winter heating of plant or building. Both low and high pressure condensing type steam turbines are in such use.

Figures 6, 7, 8 and 9 are introduced because they have historical significance in the development of compressors suitable for petroleum industry applications.

The machines shown were designed for Carrier Corp. by our senior design engineer who has since designed the Clark line of centrifugals.

Fig. 6 shows what was probably the first centrifugal refrigeration installation in the United States refining industry. The two units employ 450-hp electric motor drivers and have operated for the past eight years on brine cooling duty at an eastern seaboard refinery. Operating experience on these units has been highly satisfactory insofar as the centrifugal compressors are concerned. Periodic exchanger tube failures have indicated the desirability of using standard oil industry type heat exchangers and cheaper petroleum industry type refrigerant as the exchanger maintenance and refrigerant replenishment has been excessive.

Fig. 7 is probably the first United States mixed petroleum hydrocarbon gas compression installation operating from atmospheric pressure to discharge pressure above 100 psi. The discharge pressure is 125 lb gauge, four compressors of approximately 1300 hp each direct-connected to steam turbines exhausting to process are involved. The machines operate on 40 mol wt gas in a Gulf Coast butadiene plant.

Some operational difficulties were encountered. The last report we have was last December at which time water was being constantly drained from the lube oil of one of the low stage units and one set of the machines had been operating continuously for five months. Experience gained in handling this humidity laden gas points to the advisability of isolating the bearing chambers when excessive water is present in the gas stream. Auxiliary oil pumps were not, but probably should have been, incorporated in the installation.

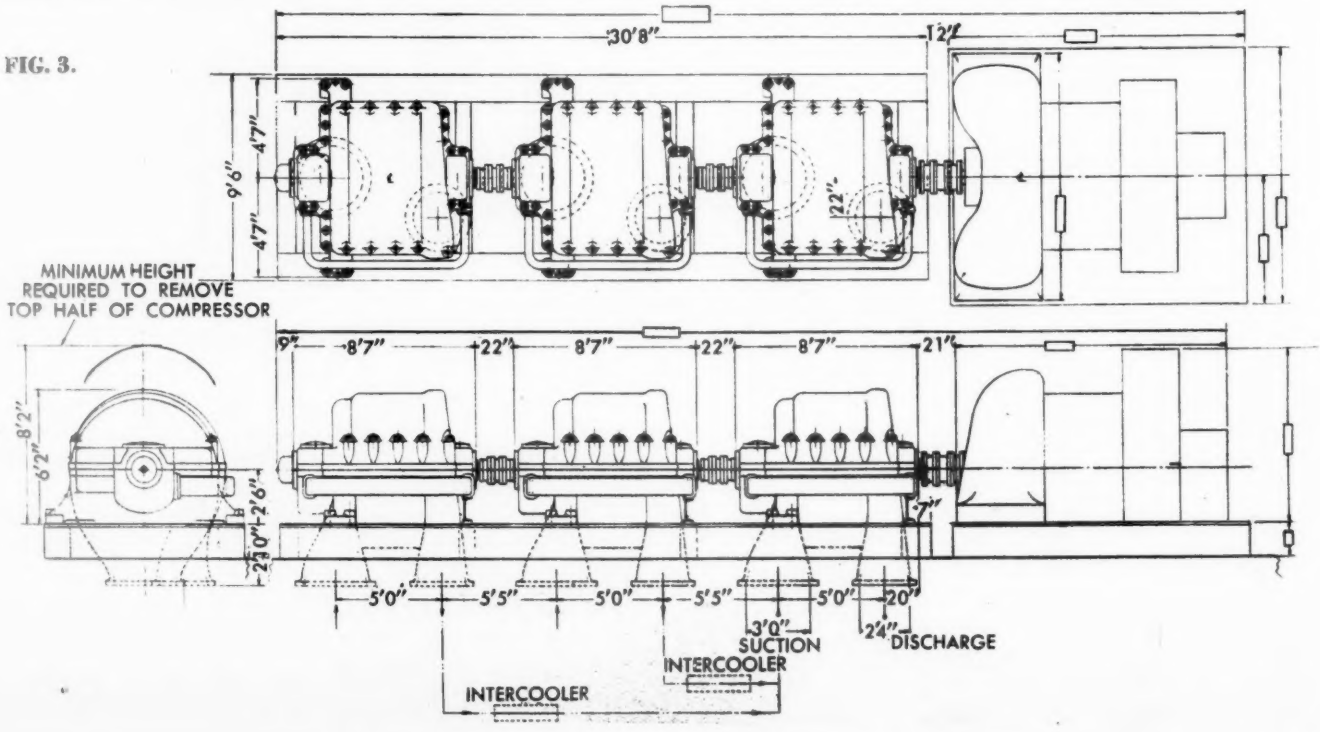
Fig. 8 is probably the first United States centrifugal air compressor installation compressing air from atmospheric pressure to pressures above 200 psi. Three stages of uncooled centrifugals are used with interstatge cooling between stages. Two 2000 hp 3 impeller machines on the first stage operate in parallel, one 4000 hp 3 impeller machine operates on the second stage and two 3000-hp 4 impeller machines operate on the third stage. The machines are synchronous motor driven through speed increasing gears. The air stream is kept free of oil by isolating the bearing chambers and three-stage compression was successfully employed with machines operating in parallel and in series on a common air stream. The installation is serving an East Coast supersonic ballistic research laboratory.

Machines in Fig. 9 are probably the first United States centrifugal refrigeration machines employing petroleum hydrocarbon as the refrigerant medium. They operate on lean oil chilling at a Gulf Coast natural gasoline plant. The machines are direct driven by 375 hp steam turbines and are significant of the trend to petroleum hydrocarbon refrigerants in centrifugal compressors.

Fig. 10 is the first test centrifugal compressor manufactured by Clark Bros. It is specifically designed for high pressure duty in the petroleum and allied industries.

During the past year a considerable number of high pressure compressors have been ordered by the petroleum industry. Quite a few propane refrigeration compressors have been ordered for lube oil dewaxing. One of the orders we have received embodies 21 compressors totaling over 70,000 hp. Air, oxygen, propane, and mixed petroleum hydrocarbons are involved. The oxygen is to be compressed to 290 psia and the mixed hydrocarbons to 275 psia. Centrifugal manufacturers have orders for other duties such as the compression of ethylene, propylene, and sulphur dioxide. A number of these machines will go on stream in the future.

FIG. 3.



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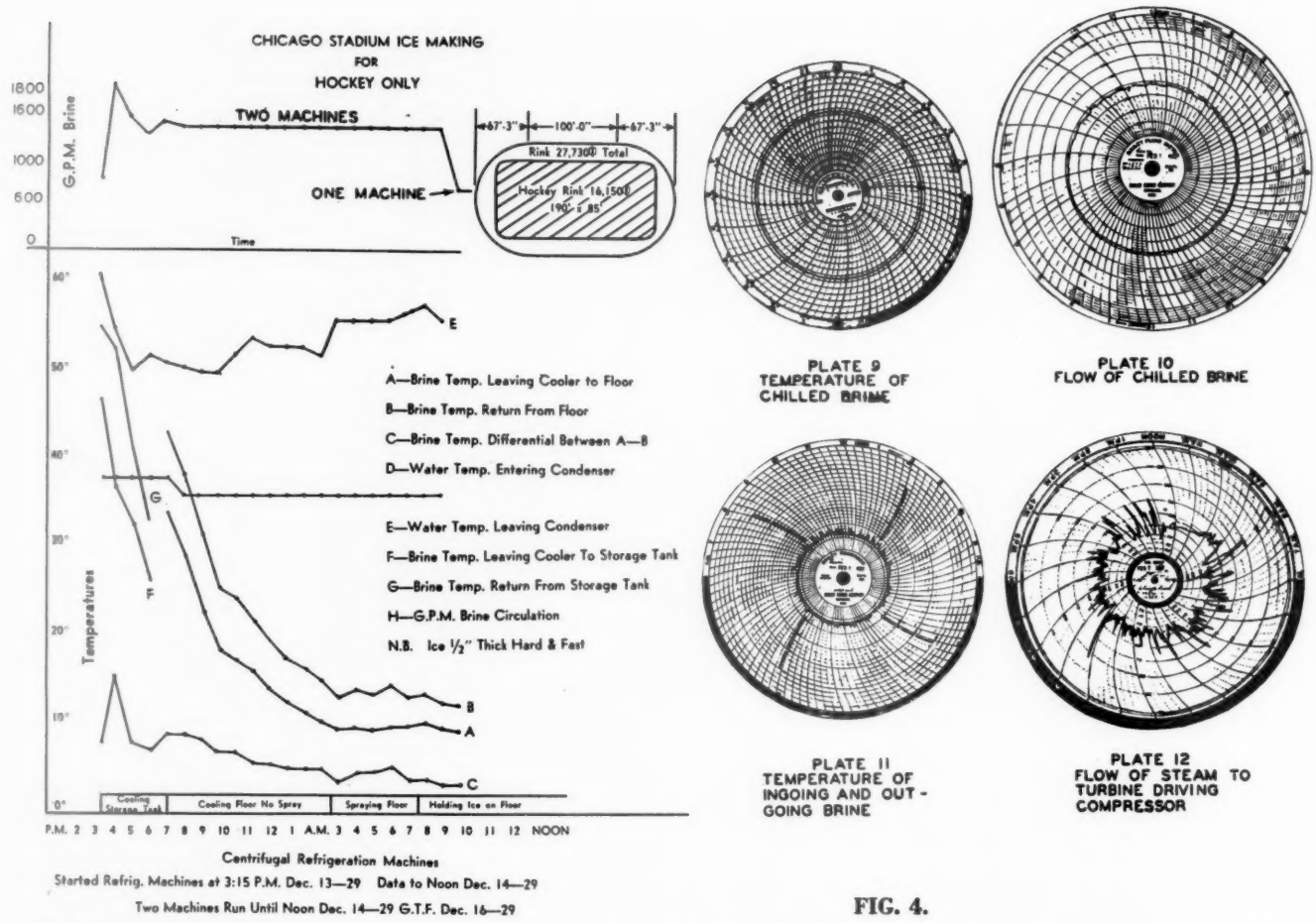
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Temperatures
Cooling Storage Tank
Cooling Floor No Spray
Spraying Floor
Holding Ice on Floor
P.M. 2 3 4 5 6 7 8 9 10 11 12 1 A.M. 3 4 5 6 7 8 9 10 11 12 NOON
Centrifugal Refrigeration Machines
Started Refrig. Machines at 3:15 P.M. Dec. 13—29 Data to Noon Dec. 14—29
Two Machines Run Until Noon Dec. 14—29 G.T.F. Dec. 16—29
PLATE 9
TEMPERATURE OF
CHILLED BRINE
PLATE 10
FLOW OF CHILLED BRINE
PLATE 11
TEMPERATURE OF
INGOING AND OUT-
GOING BRINE
PLATE 12
FLOW OF STEAM TO
TURBINE DRIVING
COMPRESSOR

FIG. 4.

It is apparent that centrifugal compressors have gained a certain degree of acceptance in the petroleum industry, and petroleum engineers are hence becoming interested in the theory and machine characteristics.

The pertinent theory and operating characteristics are not similar to reciprocating compressor characteristics and attempts to evaluate the operating characteristics of either from the other viewpoint is confusing.

Fortunately, most petroleum engineers are familiar with centrifugal liquid pumps and approach from the centrifugal liquid pump viewpoint rather than the reciprocating gas compressor viewpoint may help engineers to properly evaluate the machines. The centrifugal compressor may be called a multi-stage gas pump if you wish.

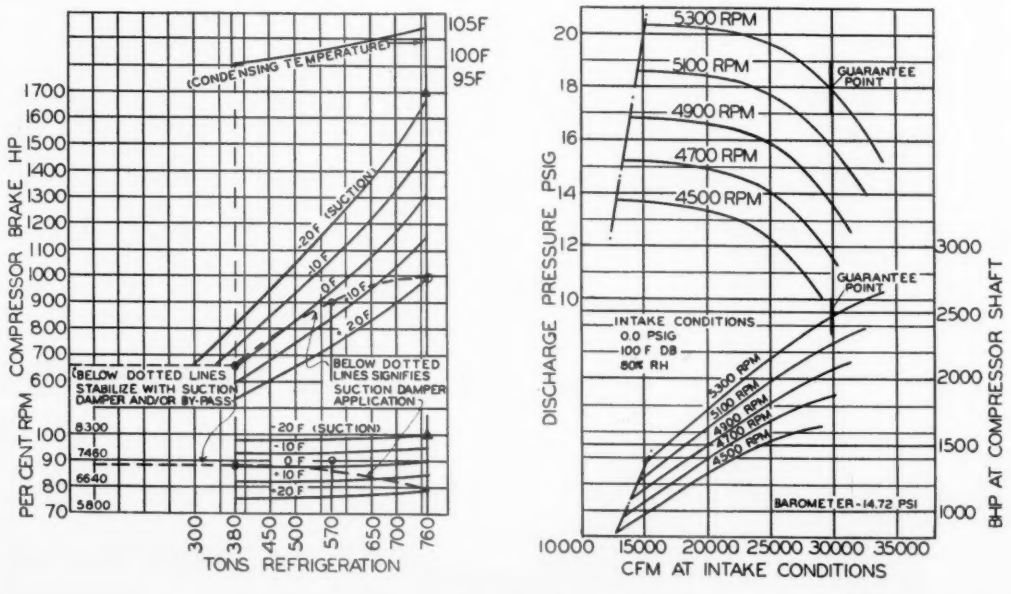
Professor Church has published a text in which he combines centrifugal pumps and compressors and successfully coveras both due to the similarity of the underlying theory.

There is one marked difference, however. As in the case of gas transmission as compared with liquid transmission volume is an additional variable that makes selections and calculations somewhat more complicated than liquid pump selection. The comparative volume, temperature and head characteristics make an interesting comparison, and are illustrated in Fig. 12.

Head of a pump or compressor, hydraulically speaking, is the number of feet of the medium being pumped, that the unit will produce while delivering its rated capacity. It may add to clarity to visualize a 4-stage water pump, that takes suction at 0 psi gauge and discharges at 800 psi gauge, capable of sustaining a water column 1848 ft in height or 1 psi gauge for each 2.31 ft of water. In the liquid pump the pressure rise per impeller is essentially the same. Temperature effect on volume and head is approximately constant on all impellers as the temperature rise is negligible. Temperature is therefore neglected on the chart and volume is constant at 100 per cent gpm as shown.

The comparative 4-stage centrifugal air compressor illustration is not of the same scale as the liquid pump illustration, the magnitude of heads being too divergent for identical scale representation. Note that 37,200 ft of air, at adia-

FIG. 5.



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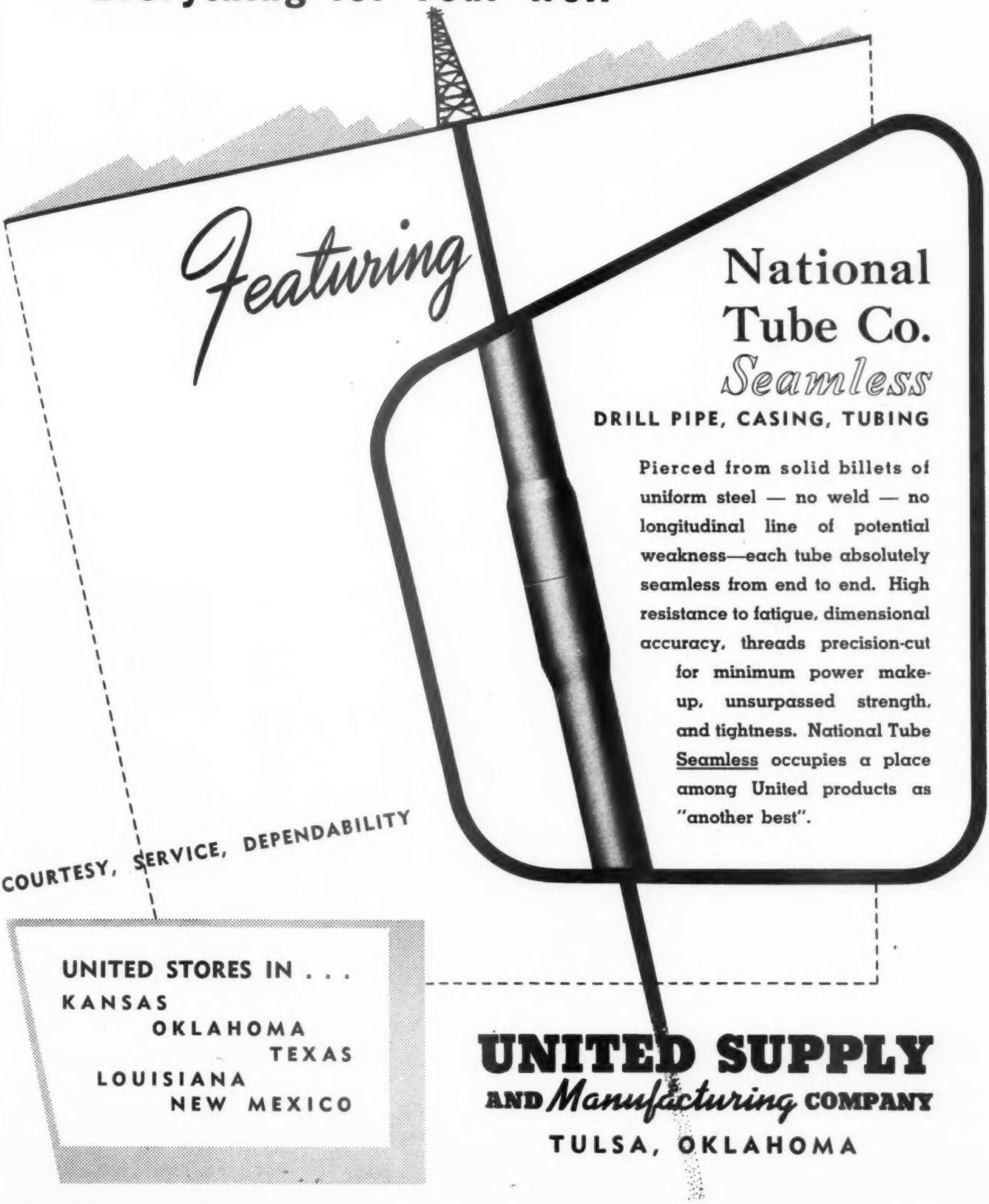

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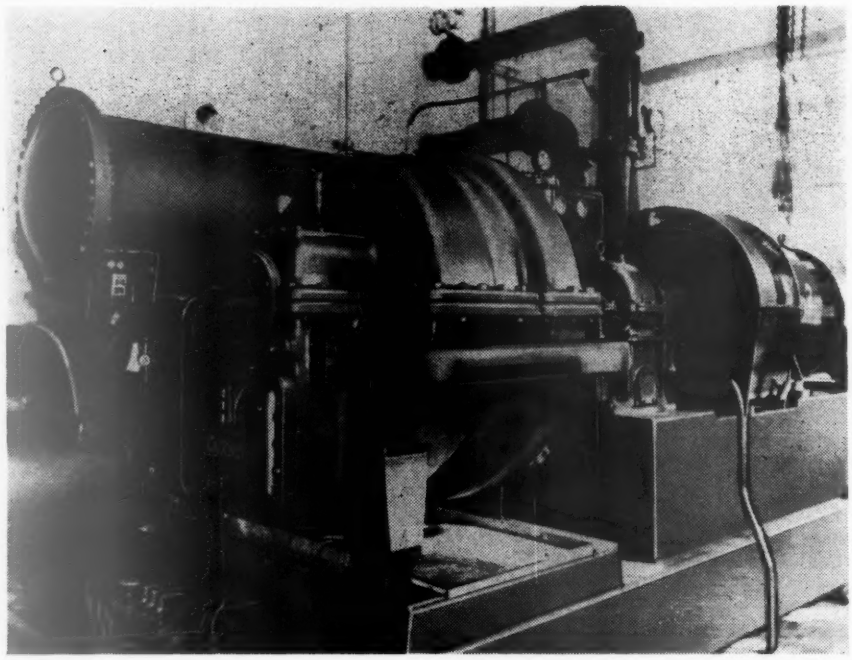


FIG. 6.

batic compression conditions, is equivalent to 26.3 psi pressure differential while only 1848 ft of water is equivalent to 800 psi gauge pressure differential.

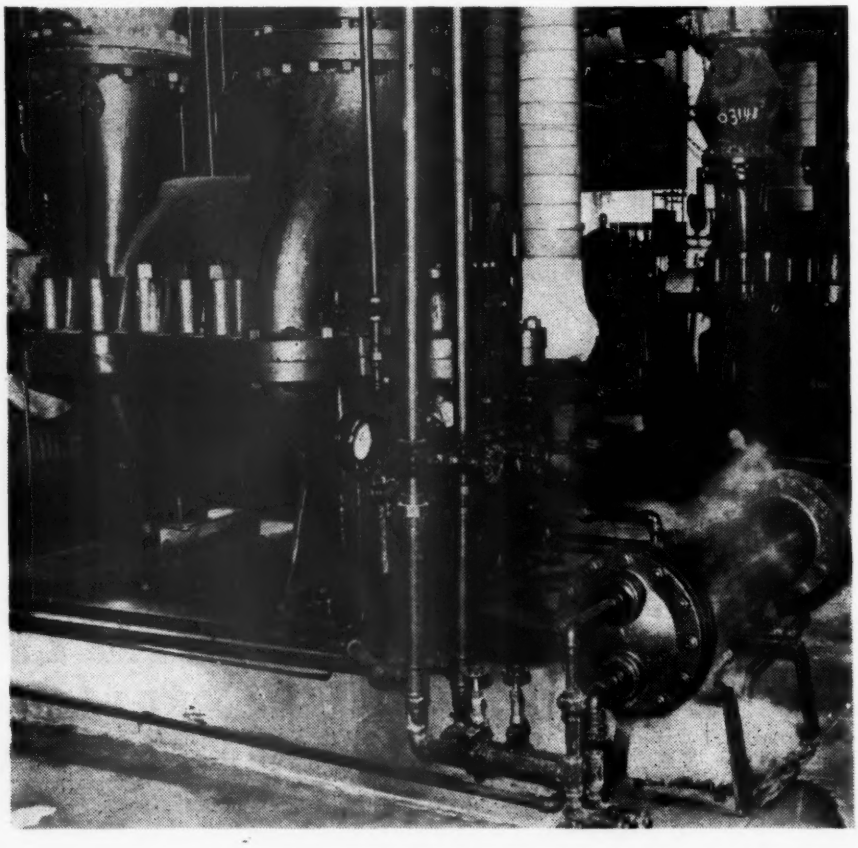
Pressure ratio of 2.8 is taken for illustrative purposes and can be produced by a four impeller uncooled centrifugal air compressor. With 14.6 psia and 100 F inlet the 2.8 ratio is equivalent to 40.9 psia discharge pressure.

The adiabatic representation is useful in that it enables us to visualize what would take place in a frictionless or 100 per cent hydraulic efficiency compressor. The adiabatic head may be visualized as a perfectly insulated column or mine shaft extending from the earth's surface, at an elevation equivalent to 14.6 psia and 100 F, to a point 37,200 ft below where the pressure due to adiabatic compression would be 40.9 psia with the corresponding adiabatic temperature of 289 F. The weight of the air in a column of the height, temperature and pressure represented would be sufficient to produce the 26.3 psi gauge pressure differential and the temperature and pressure at quarter point elevations would be equivalent to the inlet conditions at the eye of the second, third, and fourth impellers. Adiabatic head (Fig. 13) is obtained from the familiar work formula in which volume V_1 is taken for one pound, which results in a product of feet rather than foot-pounds. In the past, most blower applications dealt with air and gases of like specific heat ratios, thereby permitting the use of the pseudo-adiabatic base with uncooled compressors. The adiabatic formulae illustrated are in general use for such applications. With the establishment of the overall head and its quartered division the pressures and temperatures are obtained by solving for pressure ratios equivalent to the proportionate heads. The formula has merely been rearranged for convenience.

Frictionless or adiabatic compression is a purely theoretical concept in an uncooled centrifugal compressor. It is necessary to bridge the gap between the theoretical concept and the polytropic process that takes place in the compressor. The term polytropic means "all heat" and is used for processes other than isothermal and adiabatic, whether temperatures and volumes lie between those of isothermal and adiabatic compression or above adiabatic as indicated in our uncooled compressor illustration. Using hydraulic efficiency that the manufacturer obtains from test and using available ratio of specific heat values the polytropic exponent may be obtained from the relationship $\frac{N-1}{N} = \frac{K-1}{K} \Big/ Eff.$ The value obtained is based on no radiation loss or gain. For gases of negligible compressibility, the familiar head formula is used in conjunction with the exponent thus obtained. (Fig 14). With relatively high molecular weight hydrocarbons at high pressures, the use of the less familiar equation is recommended as it more accurately reflects compressibility. Use of the speed formula and an average value of .55 for "U" will allow estimating selections to be made with the Clark line. It should be noted that the head per impeller expression derives from the familiar gravity relationship. Velocity squared equals 2g H. The manufacturer's application engineer makes more accurate selections by selecting "U" values from his nominal rating table and the applicable pressure and efficiency corrective factors.

Use of applicable formulae in conjunction with the polytropic exponent of compression (return to Fig. 12) gives us the head temperature and pressure relationships for polytropic compression. The losses within the compressor result in temperatures higher than corresponding adiabatic temperatures. The higher temperatures lower the specific weight of the gas and we must consequently have a greater number of feet of the lighter gas to be equivalent to a pressure differential of 26.3 psi. Approximately 5 per cent more head is required

FIG. 7.



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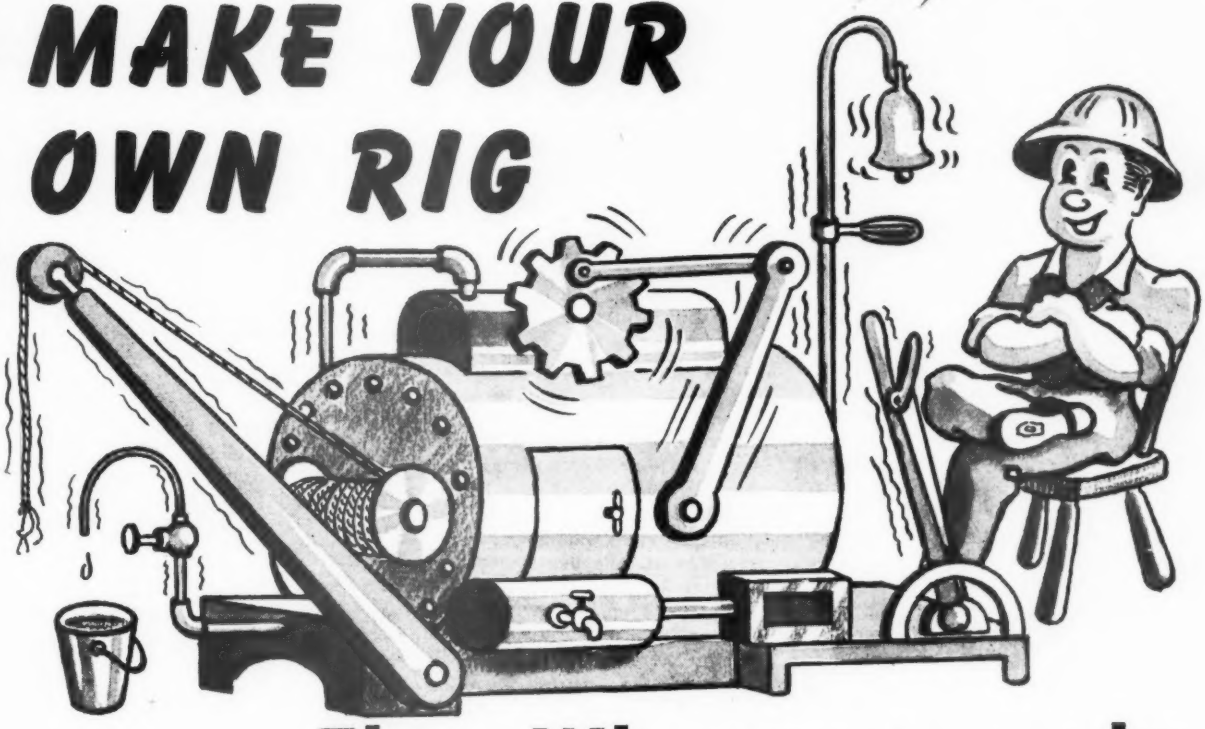

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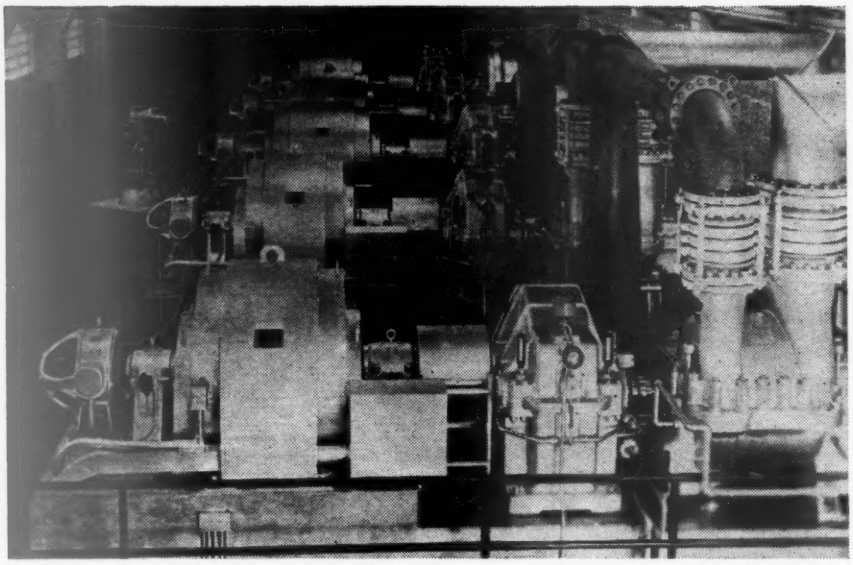


FIG. 8.

because of this higher temperature. The discharge temperature of 361 F is the temperature that would be read on a thermometer if the machine were under test. Our calculation assumed our knowing the hydraulic efficiency and no radiation loss or gain from the compressor.

While the liquid pump operates with equal pressure rise, constant volume, and approximately constant temperature through each impeller, the uncooled gas pump operates with variable pressure rise, volume and temperature. The gas pump impellers may be selected for equal diameter but the width of the impellers is decreased as we progress through the machine. The multi-stage liquid pump may employ identical impellers throughout.

With constant inlet temperature and volume the gas pump would compress from 146 psia to 409 psia or a differential of 263 psi. It is apparent that the compression ratio has remained constant with the increased inlet pressure and horsepower has increased in the approximate ratio of 10 to 1. The liquid pump would continue to deliver 800 psi differential with increased suction pressure and horsepower would remain substantially the same. Neglecting viscosity, both the centrifugal gas pump and liquid pump are independent of density as regards head. The centrifugal gas pump will develop the same head whether handling hydrogen or mercury vapor. The pressure ratios for a given head or number of impellers vary markedly, however. (Fig. 15). It will be noted that a 5 impeller compressor will produce a pressure ratio of approximately 2 to 1 when compressing methane, whereas the same number of impellers (or head) will produce approximately 12 to 1 when compressing butane.

The 700 ft per sec peripheral speed given in the tabulation is quite conservative. Tip speeds of the magnitude of 750 to 775 ft per sec will be more normal. These tip speeds are four to five times those normally employed for liquid pumps and consequently result in a much more rugged machine as the gas pump is designed for the higher stresses involved.

We have covered head as related to water pumps, and uncooled centrifugal air compressors for both the psuedo-adiabatic and actual polytropic base.

Iso-thermal compression and gasses, other than air, should be considered in order to round out the picture. Iso-thermal implies compression without temperature rise. With an infinite amount of intercooling, we may approach but not reach iso-thermal compression. Some European manufacturers design their centrifugal air compressors for a high degree of intercooling between impellers as power cost is, generally speaking, of greater economic significance there than is the case in the United States. The degree of cooling achieved is such that air compression, temperatures and volumes fall between iso-thermal and adiabatic. As use of either process results in the selection of a psuedo-base, iso-thermal is apparently chosen for simplicity of calculations.

It will be noted that with equal pressure ratios (Fig. 11) the deviation from adiabatic for uncooled centrifugals are by no means constant. We have a 5 per cent variation with air, a 4 per cent variation with sulphur-dioxide and a 2.1 per cent variation with propane. The gravity of the gas does not explain this variation as sulphur dioxide with the higher gravity has a greater variation than propane. The ratio of specific heats seems to have the most marked effect. The second column for propane shows the effect on head when compressibility is figured for the compressor discharge condition. The inlet and outlet pressures used in the calculations are in the range of commercial applications.

The efficiency variations are given in points of efficiency. Three and a half points for air, two and eight-tenths for sulphur dioxide and one and six-tenths for propane. It is apparent that the use of efficiencies related to the adiabatic base would result in a discrepancy of one and eight-tenths per cent for propane. In other words, our adiabatic ef-

FIG. 9.

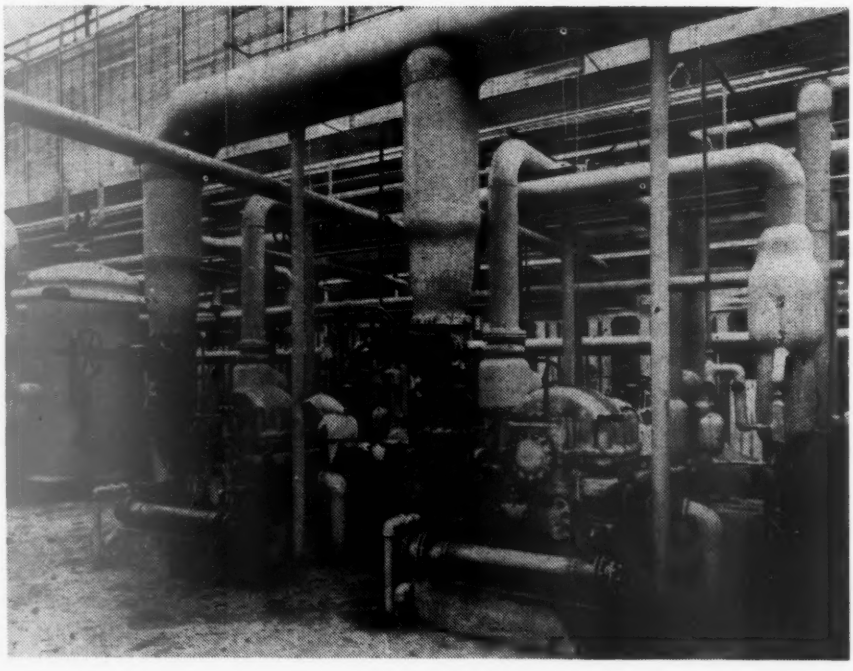
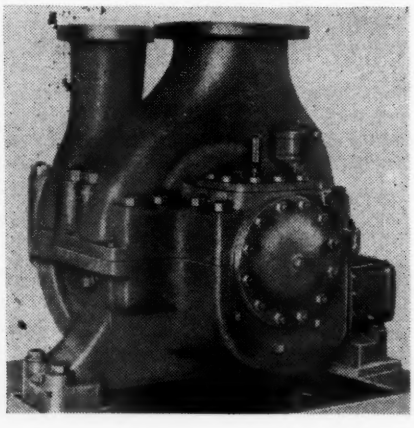


FIG. 10.



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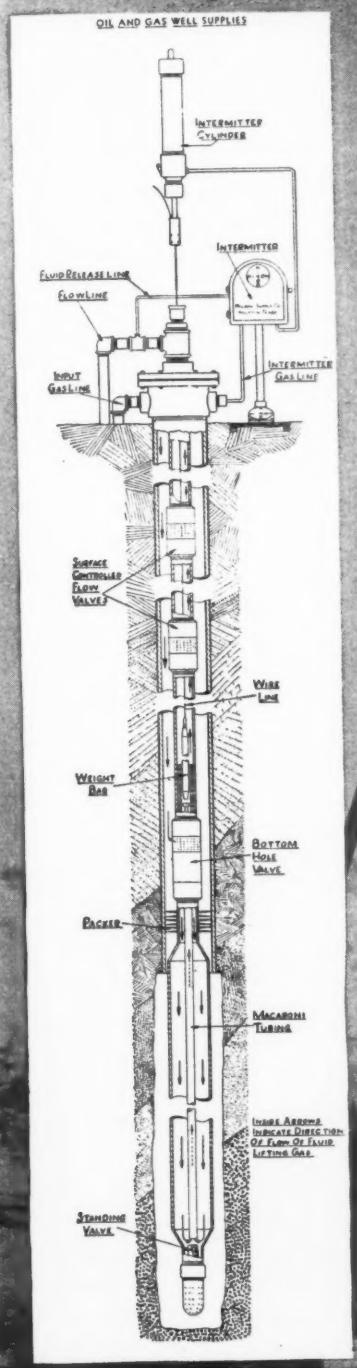

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FIG. 11. Deviation from adiabatic uncooled centrifugal compressors.

	Air		SO_2		Propane		Propane	
Relative gravity	1.0		2.215		1.52		1.52	
Compression ratio	2.8		2.8		2.8		2.8	
CFM at inlet	26,000		6,150		5,830		5,830	
Inlet, psia	14.6		40.3		89.3		89.3	
		26.3		72.7		160.7		160.7
Discharge, psia	40.9		113.0		250.00		250.00	
Inlet temperature, °F	100.0		60.0		48.0		48.0	
		261.0		144.0		99.0		97.0
Discharge temperature, °F	361.0		204.0		147.0		145.0	
Specific volume cu./ft. lb inlet	14.82		2.05		1.165		1.165	
Specific volume cu/ft lb outlet							.46	
Polytropic, "N"	1.593		1.38		1.21		1.203	
Adiabatic "N"	1.395		1.256		1.15			
Isothermal "N"	1.0		1.0		1.0			
Polytropic head, ft	39,050		14,180		16,880		16,300	
		5.0%		4.0%		2.1%		
Adiabatic head, ft	37,200		13,630		16,520			
Isothermal head, ft	32,100		12,280		15,410			
Polytropic efficiency (base)	76.0		74.0		74.0		74.0	
		3.5%		2.8%		1.6%		
Adiabatic efficiency	72.5		71.2		72.4			
Isothermal efficiency	62.5		64.0		67.5			
Hudraulic horsepower	2,800		1,740		3,460		3,340	
Weight flow, lb/min	1,800		3,000		5,000		5,000	

ficiency for propane would be 70.6 per cent instead of 72.4 per cent.

It would appear that the great variety of gases, with varying specific heat ratios and compressibility characteristics, that could conceivably be compressed centrifugally will require some special consideration if inaccuracies in horsepower and speed calculations are to be avoided.

It is recognized that the use of an adiabatic base and of Mollier diagrams permits rapid calculations of compression horsepower requirements, and is favored by engineers in the industry. With reciprocating compressors the variation between the psuedo-adiabatic base and the actual is small with water-jacketed cylinders, and adiabatic therefore provides the required accuracy. Uncooled centrifugals cannot be selected with accuracy on an adiabatic basis if gases of widely divergent specific heat ratios are to be accommodated from the same rating data. Practically all the losses in an uncooled centrifugal tend to heat the gas and accentuate the variations. Mechanical losses are only external losses and seldom exceed 1 per cent.

As was pointed out for European air compression practice, any base will give a certain degree of accuracy if the gases to be handled are of like specific heat ratio and compressibility is also a negligible factor.

Personal experience with the use of the actual polytropic concept and hydraulic efficiency as used by hydraulic turbine and pump designers does not render us unmindful of the point that an adiabatic air or equivalent base could be used and corrective factors employed for the gases that deviate excessively from air. It has been felt that the use of such factors will prove more cumbersome, in the future, than solving for polytropic or temperature rise exponent.

When working with the actual head, one set of rating curves will suffice (Fig. 17) if the application engineer will avoid exceeding sonic speed with the gas to be compressed. The critical condition exists at the impeller inlet and results in the phenomenon sometimes referred to as the stonewall. Note that the curves are plotted for polytropic head versus first impeller inlet cfm. The constant speed curves are plotted in per cent of nominal rpm. As the speed and head is increased, the surge point moves over toward the stonewall thereby decreasing the stable range of operation. With air and low molecular weight gases we do not normally encounter this sonic speed phenomenon and the head curves carry out in a manner similar to the 95 per cent nominal speed and below curves with a resultant wider range of stable operation.

We previously spoke of the dissimilarity of the centrifugal machine operating characteristic when compared with the reciprocating compressor. The dissimilarity is such that one type's strength becomes the other's weakness. The strength of the centrifugal lies in its ability to handle wide capacity variations with slight head variations. Fig. 17 shows a 44.8 per cent capacity decrease with 23 per cent increase in head at 100 per cent nominal speed. The 23 per cent increase is excessive for petroleum hydrocarbon compressors that have less backward blade curvature and do not crowd the stonewall. Percentagewise, the increase in head is also on the high side for high compression ratios that obtain on low temperature refrigeration applications and natural gas compression requirements that could conceivably involve compression ratios as high as 20 to 1. A recent check on a problem of this nature revealed that with approximately 14 lb abs inlet pressure and 300 lb abs discharge pressure, an increase in suction pressure of 5 lb would require an average speed reduction of approximately 6 per cent with discharge pressure and weight flow remaining constant.

From the illustration it will be observed that 9.3 per cent speed reduction will reduce the volume from 3080 cfm to 1360 cfm, with a constant head of 7000 ft before reaching the surge point. This is a volume or weight flow reduction of 55.8 per cent with only 9.3 per cent speed reduction. If stability is the prime consideration, the compressor could be operated at constant speed and the 23 per cent increase in head could be employed in suction throttling which would increase the vapor volume at the compressor inlet, which in turn moves the operating point to the right and provides stability with even lower weight flow than the 44.2 per cent obtainable with speed reduction.

Engineers are familiar with the laws that apply to centrifugal fans, pumps, and compressors, viz.—volume varies as the first power of speed, head as the square of speed and horsepower as the cube of speed.

It is sometimes erroneously assumed that if speed and volume changes as the first power, the head must change as the square of the speed and the horsepower must vary as the cube of the speed change. This approach overlooks the system characteristic that the centrifugal machine has to contend with. In a system where head is composed entirely of frictional resistance, and since pressure drop varies approximately as the

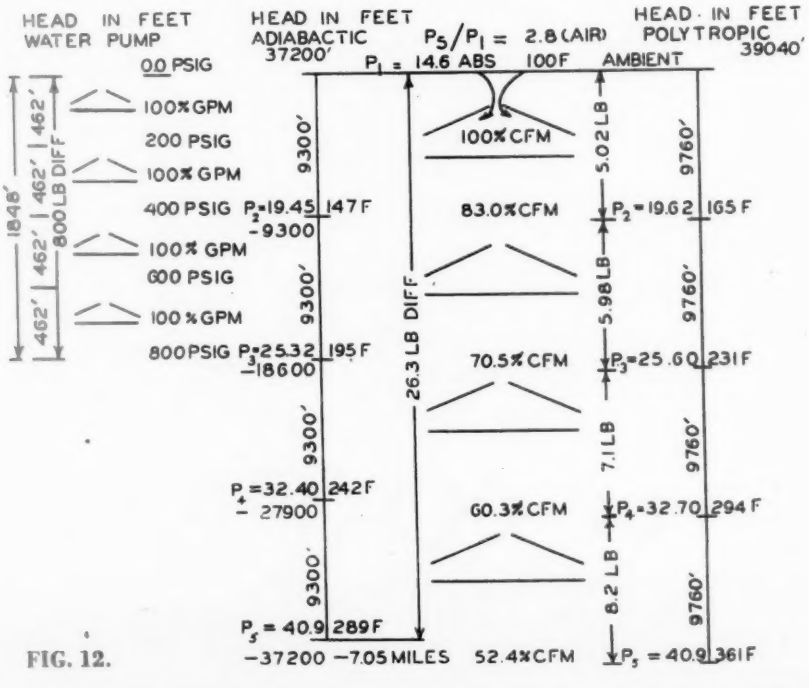
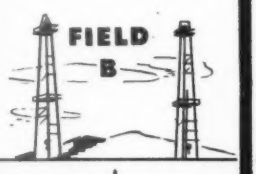
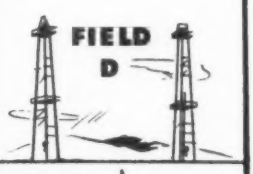


FIG. 12.

Another Example of Increased Production with BLACK MAGIC OIL BASE DRILLING FLUID

COMPARE THESE 8 OFFSETTING WELLS IN 4 SEPARATE FIELDS. Each well completed with Black Magic is compared with an offset well completed with a conventional water base mud. In each comparison the factors governing production closely parallel one another—such as chokes, permeability, pressures, etc. Only in *production figures* do the wells lack similarity. *Black Magic is the deciding factor here.*





	FIELD A		FIELD B		FIELD C		FIELD D	
	BLACK MAGIC	WATER BASE	**BLACK MAGIC**	WATER BASE	**BLACK MAGIC**	WATER BASE	**BLACK MAGIC**	WATER BASE
Initial Production—Bbls. Day	**1563**	558	**369**	330	**1575**	1030	**374**	88
Productivity Index	**1.42**	0.144	**250.**	60.	**5.73**	1.22	**7.5**	0.98
Producing Zone Interval	**110′**	90′	**178′**	170′	**270′**	260′	**35′**	31′
Permeability, Approx.	**60m.d.**	60m.d.	**600m.d.**	600m.d.	**300m.d.**	300m.d.	**2400m.d.**	2400m.d.
Bottom Hole Pressure, psi	**3635**	3580	**2250**	2370	**1834**	1450	**136**	110
Later Production Bbls./Day (Comparable Restricted Chokes)	**311**	125	**350**	284	**525**	282	**423**	65

THESE ARE NOT UNUSUAL EXAMPLES. In almost every instance where data is available, wells drilled with Black Magic show greater production, not only at the time of completion, but many months later, and production curves at the end of two and three year periods are on the average even more amazing.

Water in the producing zone restricts the free flow of crude oil, lessening the ultimate recovery of oil from the well. This is commonly referred to as "water blocking" or "mudding off." By capillary action and hydrous swelling of the formation, water particles actually seal up minute crevices in oil sands and even under extreme pressures the water is never completely dislodged.

Black Magic has a zero filtrate loss, forms only a paper thin mud cake, which is completely taken off by crude oil, eliminating blocking off the pay section.

In addition, cement, salt, anhydrite, gypsum and limestone will not affect it. No chemicals are needed to maintain the properties of Black Magic. Core recovery is higher than with any other drilling fluid and accurate values are obtained. Black Magic lubricates bit bearings, allows longer bit time on bottom, keeps a hole "to gauge" and eliminates conditions causing stuck pipe. Black Magic may be regenerated and used over and over again. When properly used it is one of the most economical commodities in the entire drilling operation.

Write for "Oil Base Drilling Fluids"— an informative paper delivered at 75th annual meeting of A.I.M.E.; and Black Magic Catalog.

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OIL BASE, INC.

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FIG. 13

For normal air and perfect diatonic gases the following adiabatic formulae are in general usage:

$$\frac{C_p}{C_v} = 1.3947 = K \qquad \frac{K-1}{K} = \frac{.3947}{1.3947} = .283$$

$$R = \frac{1544}{28.95} = 53.34$$

$$X = \left(\frac{P_2}{P_1}\right)^{.283} - 1$$

Values of X have been tabulated by Moss and Smith for normal air and perfect diatomic gases.

Mean effective pressure ratio:

$$\text{"b"} = \frac{1}{.283}(X) \text{ or } \text{"b"} = \frac{K}{K-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}} - 1\right]$$

$$\text{Adiabatic head} = \frac{1}{.283} 144\ P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{.283} - 1\right] \text{ or}$$

$$H_a = 144\ P_1V_1 \times \text{"b"}$$

$$\text{Adiabatic HP} = \frac{1}{.283} \times \frac{144}{33{,}000} \times \frac{CFM \times P_1 \times X}{Eff}$$

$$= \frac{.01542 \times CFM \times P_1 \times X}{Eff}$$

$$HP = \frac{\text{Wt. flow \#/min.} \times \text{head}}{33{,}000 \times Eff}$$

$$= (\#\ \text{Min.} \times V_1) \times \frac{(144)}{(33{,}000)} \times \frac{P_1 \times \text{"b"}}{Eff}$$

$$= \frac{CFM \times P_1 \text{ "b"}}{229.17 \times Eff}$$

$$\text{"b"} = \frac{(U_2)^2 \times \text{No. impellers} \times \text{Pressure coefficient}}{(32.2 \times 53.34) \times T}$$

$$U_2 = \sqrt{\frac{\text{"b"} \times 1725 \times T}{u \times \text{No. impellers} \times \text{Relative gravity}}}$$

$$U_2 = \frac{\pi D N}{720} \qquad n = \frac{720 \times U_2}{\pi D}$$

Adiabatic formula

$$(r)^{.283} = \frac{.283 \times \text{adiabatic head}}{144\ P_1V_1} + 1$$

$$T_2 = T_1\ (r)^{.283}$$

FIG. 14

Polytropic formulae

$$\text{Polytropic exponent} = \frac{N-1}{N} \text{ (uncooled)}$$

$$\frac{N-1}{N} = \frac{K-1}{K} \text{/Hydraulic efficiency} \qquad \frac{K-1}{K} = .283$$

$$= .283/.76 = .372 \text{ (for air)}$$

$$\text{Polytropic head} = \frac{144\ P_1V_1}{\frac{N-1}{N}}\left[\left(\frac{P_2}{P_1}\right)^{\frac{N-1}{N}} - 1\right]$$

$$(r)^{\frac{N-1}{N}} = \frac{\frac{N-1}{N} \times \text{Polytropic head}}{144\ P_1V_1} + 1$$

$$T_2 = T_1\ (r)^{\frac{N-1}{N}}$$

From the gravity relationship $(U_2)^2 = 2\ gH$

$$\text{Head /Impeller} = \frac{\text{Pressure coefficient} \times (U_2)^2}{32.2}$$

$$n = \frac{1300}{D}\sqrt{\frac{\text{Head/Impeller}}{U}}$$

$$\text{Isothermal head} = 144\ P_1\ V_1\ 2.302\ \text{Log}_{10}\ (r)$$

$$\text{Polytropic head} = \frac{144 \times 2.302}{2}[P_1V_1 + P_2V_2]\ \text{Log}_{10}\ (r)$$

$$= 165.7\ [P_1\ V_1 + P_2V_2]\ \text{Log}_{10}\ (r)$$

T = Absolute temperature
U_2 = Impeller peripheral speed in feet per second
n = Revolutions per minute
D = Diameter impeller in inches
U = Pressure coefficient product of centrifugal action in impeller and conversion of velocity pressure to static pressure in diffuser. Varies with blade angle and other factors between .5 to .6
r = Ratio of compression $\frac{P_2}{P_1}$
R = Gas constant = $\frac{1544}{\text{mol. weight}}$
H_a = Adiabatic head in feet
g = Gravity = 32.2
π = 3.1416
N = Polytropic exponent of compression
$K = \frac{C_P}{C_v}$ Adiabatic exponent

square of volume or velocity, this approach is not far off. Most systems, however, are composed of fixed pressure differences that are of far greater magnitude than the frictional head. Large differences in flow in such systems do not appreciably affect the overall head. It will be recognized that the centrifugal compressor characteristic matches a system characteristic of this type, i.e., large flow variation with slight change in head.

Depending upon the system characteristic, the centrifugal may be automatically made to operate at any point to the right of the surge line on any of the speed curves if provided with variable speed. It is a simple matter to provide such control with turbines. With constant speed motor drive it is a question of economics as to whether the incremental cost of hydraulic couplings or magnetic couplings will pay out over

FIG. 15. Centrifugal compressors compression ratios.*

(14.7 psia, 100°F entr. cond.)

No.	Gas	Mo. wt.	2 impellers		3 impellers		4 impellers		5 impellers	
				P_2/P_1		P_2/P_1		P_2/P_1		P_2/P_1
1	Air	29	Max.	1.70	Max.	2.13	Max.	2.64	Max.	3.19
			Min.	1.62	Min.	2.01	Min.	2.45	Min.	2.94
2	Methane CH_4	16	Max.	1.36	Max.	1.57	Max.	1.80	Max.	2.05
			Min.	1.33	Min.	1.51	Min.	1.72	Min.	1.94
3	Natural Gas	20	Max.	1.46	Max.	1.75	Max.	2.13	Max.	2.43
			Min.	1.42	Min.	1.67	Min.	1.95	Min.	2.26
4	Ethylene C_2H_4	28	Max.	1.69	Max.	2.15	Max.	2.70	Max.	3.34
			Min.	1.62	Min.	2.03	Min.	2.50	Min.	3.06
5	Ethane C_2H_6	30	Max.	1.76	Max.	2.26	Max.	2.88	Max.	3.6
			Min.	1.68	Min.	2.12	Min.	2.65	Min.	3.28
6	Propylene C_3H_6	42	Max.	2.19	Max.	3.12	Max.	4.35	Max.	5.95
			Min.	2.06	Min.	2.85	Min.	3.89	Min.	5.23
7	Propane C_3H_8	44	Max.	2.27	Max.	3.28	Max.	4.63	Max.	6.40
			Min.	2.13	Min.	2.97	Min.	4.13	Min.	5.58
8	N-Butane C_4H_{10}	58	Max.	2.96	Max.	4.82	Max.	7.65	Max.	11.80
			Min.	2.72	Min.	4.25	Min.	6.52	Min.	9.80
9	Isobutane C_4H_{10}	58	Max.	2.96	Max.	4.82	Max.	7.65	Max.	11.80
			Min.	2.72	Min.	4.25	Min.	6.52	Min.	9.80

*"U" value at max. = 57.
*"U" value at min. = .52.
Impeller tip speed = 700 ft/sec.

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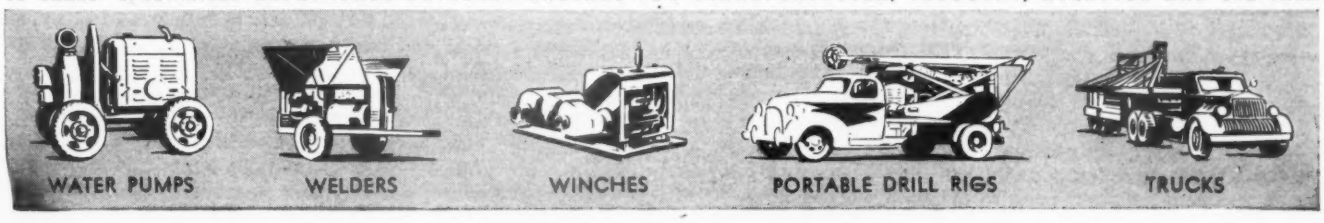

simpler suction throttling. It its apparent that such devices operate at optimum efficiency when coupled with the centrifugal characteristic which keeps coupling losses to a minimum because of the slight speed reduction required for large capacity variations. With constant speed the compressor will operate at any volume to the right of the surge point on the 100 per cent nominal speed curve or any other single curve for that matter. Further stability is obtainable by means of suction throttling as previously mentioned.

It is apparent that machines with such

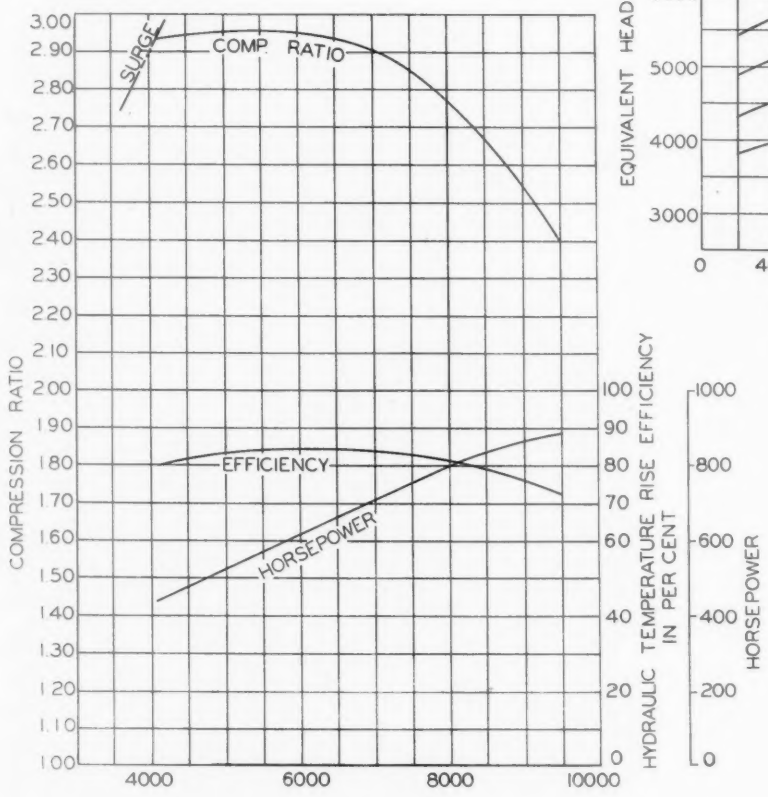

FIG. 16.

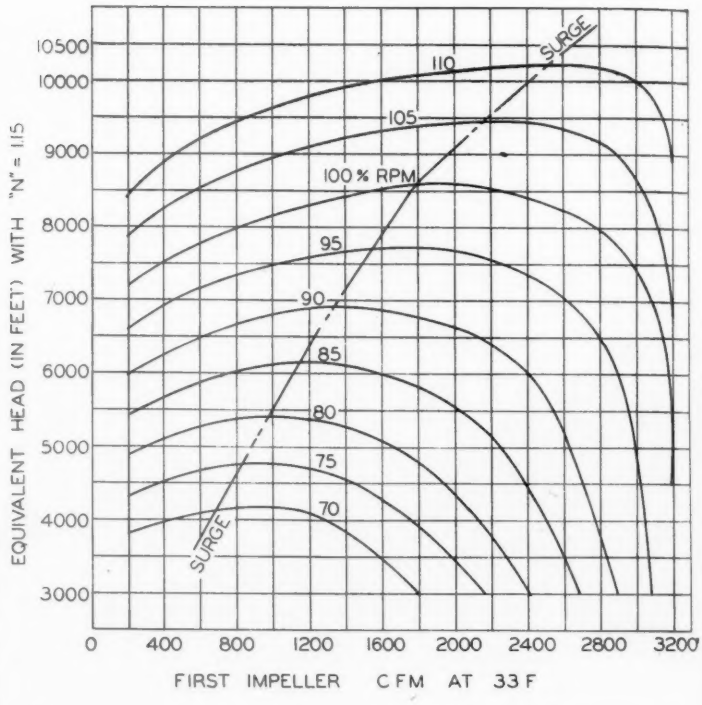

FIG. 17.

a relatively flat head characteristic are sensitive to head variations. It is for this reason that the centrifugal application engineer thinks in terms of head and carefuly selects the rotative speed that will produce the required head. The reciprocating application engineer, on the other hand, gives due consideration to volumetric efficiency which is relatively unimportant in centrifugal selections. The reciprocating machine may be said to have a relatively flat volume characteristic at a given speed as its head varies over a wide range with slight changes in volume. The reciprocating compressor is sensitive to volume and is often furnished with clearance pockets or speed variation. The centrifugal is sensitive to speed and is more often furnished with variable speed and suction throttling than with bypass.

It is important that a centrifugal machine and its driver be selected for a speed that will permit the compressor to deliver the required pressure differential with the minimum gravity gas the machine will be called upon to handle. If this precaution is taken (Fig. 4) there need be no fear of the machine's coping with variable head or pressure conditions. The operating charts were taken concurrently and illustrate the capacity surges that can be handled by a centrifugal machine while maintaining close control of temperatures or pressures in process. Note that the load on the driver varies in the ratio of 80 to 20 or 4 to 1 as indicated by steam flow. These fluctuations in load are accompanied by rapid changes in head to which the machine responds almost instantaneously through the medium of a relatively simple control device.

Still wider ranges of head and pressure are met on certain intermittent duties such as skating rinks. Machines are called upon to start chilling the brine tank at a relatively high temperature level of 55 F and pull down to 25 F. As indicated by curve "A," the final brine temperature is approximately 10 F giving a range of 45 F. This is a duty that imposes a hardship on the centrifugal compressor and reciprocating type compressors are unquestionably better adapted if the operation is continuous. Two other well known stadiums, Madison Square Garden and Atlantic City Convention Hall, have likewise employed centrifugals for this duty for more than 15 years. The N.A.C.A. wind tunnel in Cleveland employs 21,000 hp of centrifugals over an even wider range of temperatures.

Whereas continuous duty and high power costs would undoubtedly favor reciprocating equipment for such duties, it is of interest to note that centrifugals can be adapted to such an unfavorable duty and that Madison Square Garden has purchased centrifugals again after approximately 20 years operating experience with such an arrangement.

Performance curves for machines that take suction at constant pressure normally plot cfm at constant inlet condition against discharge pressure as illustrated in Fig. 5. Corrective factors for varying inlet temperatures may be employed. The curve on the right is illustrative of such performance curves.

The operating characteristics of a centrifugal compressor on a refrigeration cycle can be best represented by plotting varying suction temperatures against horsepower and capacity as shown in the upper half of the curve at the left (Fig. 5), and varying suction temperatures against per cent rpm and capacity as shown below. Note that at 100 per cent capacity approximately 21 per cent speed reduction is required to raise the suction temperature from minus 20 F to plus 20 F, or a range of 40 F. At 50 per cent capacity only 12 per cent speed reduction supplemented by suction throttling is employed in order to avoid surging.

In addition to head and discharge pressure, pressure ratio as illustrated in Fig. 16 may be plotted against inlet cfm at a given inlet temperature. Performance curves in this type may prove to be of more use to the customer on gas com-

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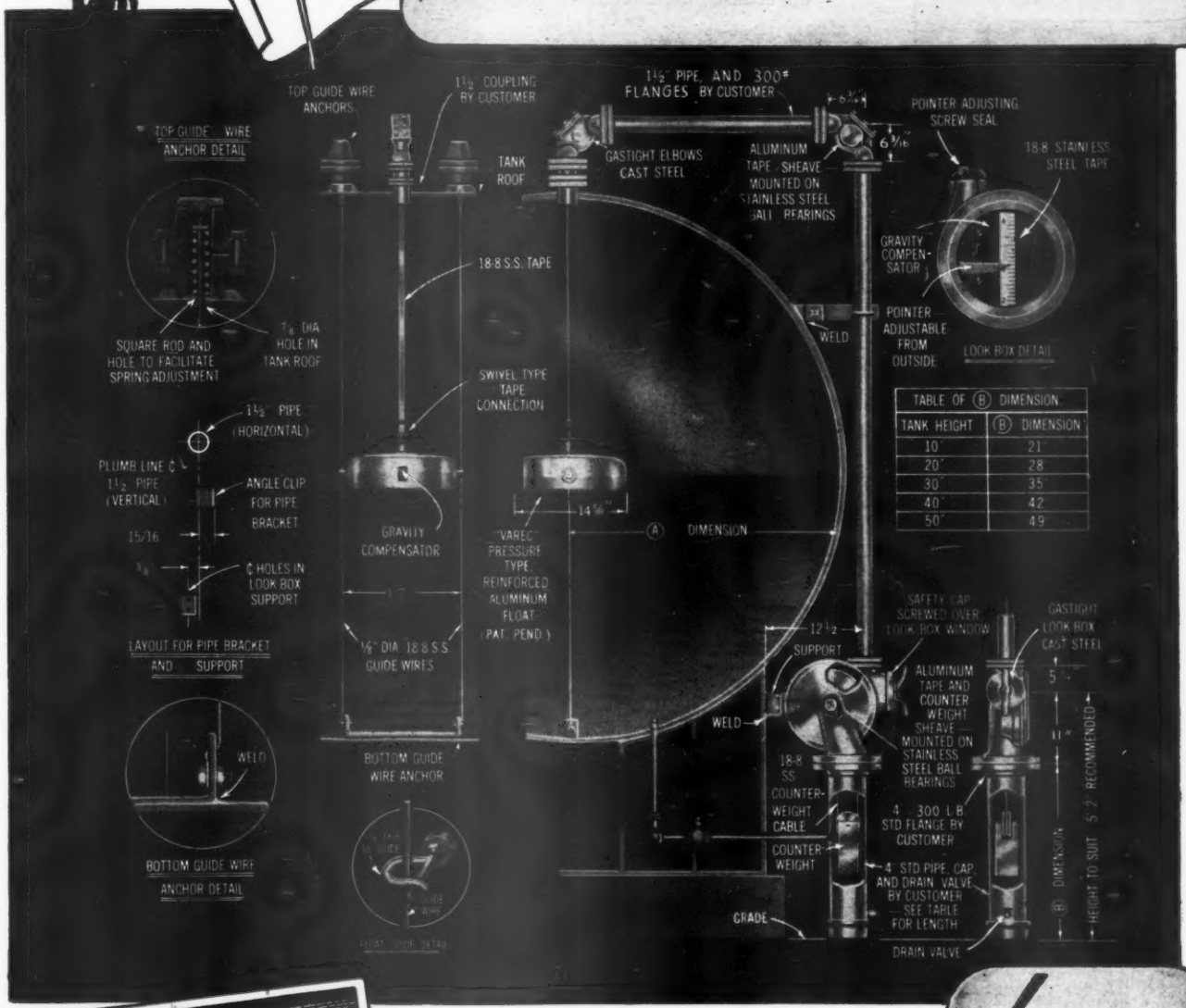
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PLUMB LINE ℄ 1½" PIPE (VERTICAL)
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DRAIN VALVE
Ⓑ DIMENSION
HEIGHT TO SUIT 5'-2" RECOMMENDED

TABLE OF Ⓑ DIMENSION	
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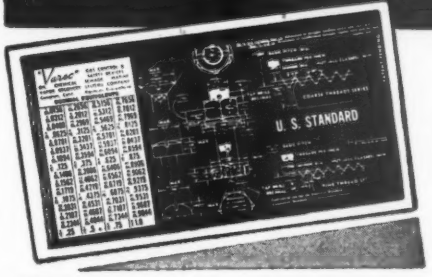
20'	28"
30'	35"
40'	42"
50'	49"



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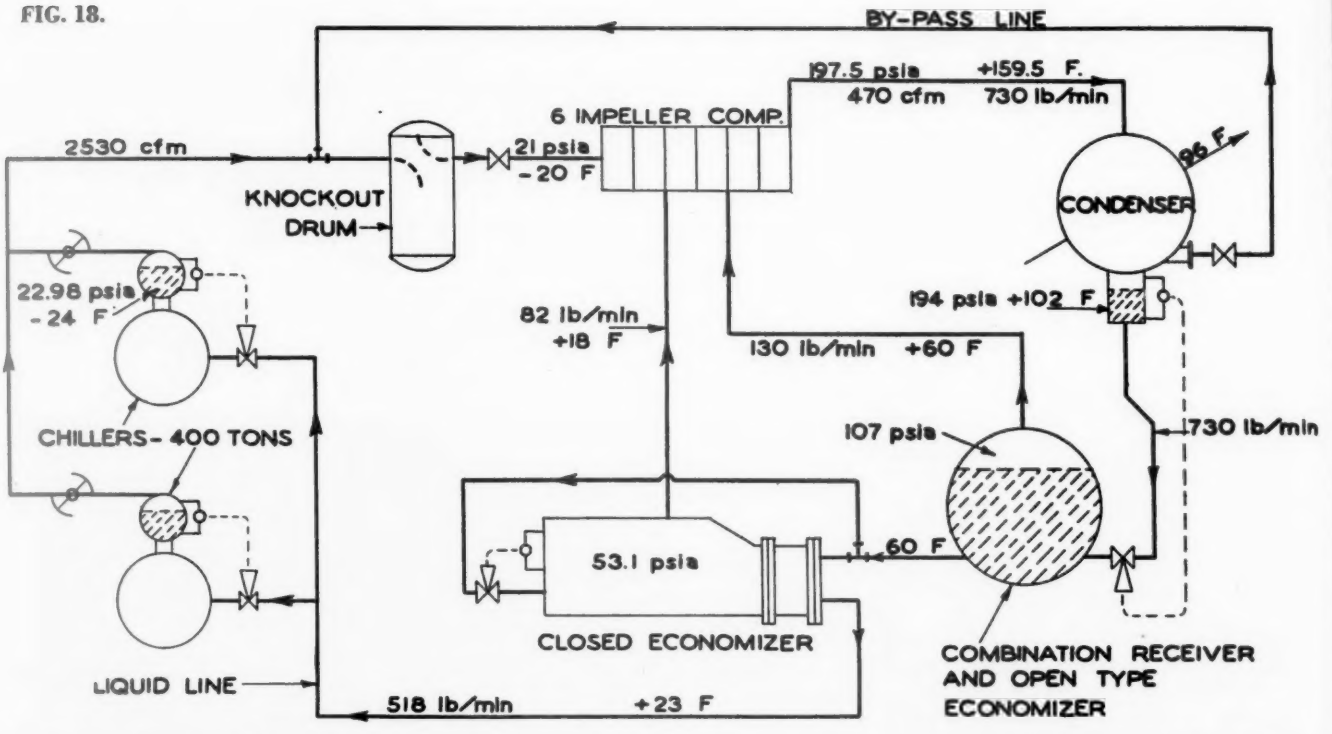
Depending upon which is the governing authority

FIG. 18.



pression applications, if the suction pressure is subject to variations. Note that the pressure ratio is 2.55 when handling 9000 cfm. The surge point is at 4100 cfm volume or 45.5 per cent. The 54.5 per cent increase in volume from surge point to 9000 cfm is accompanied by a reduction in pressure ratio from 2.93 to 2.55, or 13 per cent while the corresponding head reduction is equivalent to 15 per cent. This value corresponds to the previous 23 per cent increase in head given for the compressor with impeller blades of more backward curvature. When the 23 per cent factor is adjusted for equal stability range and head reduction rather than increase, the value becomes 24 per cent as compared to 15 per cent. This is to be expected as greater backward curvature of impeller blades results in a more drooping characteristic curve.

Note that although the compressor shows a maximum hydraulic efficiency of 84 per cent, the efficiency at the selection point is 76 per cent. This is another inherent difference in centrifugal and reciprocating compressors. For reasons of stability and ofttimes maximum efficiency at normal operating condition, the centrifugal is not picked at its most efficient point. This results in relatively higher full load power for the centrifugal than for a reciprocating installation. Whereas the reciprocating compressor shows to best advantage by comparing at full load and maximum pressure ratio, the centrifugal gains efficiency at part load, within the range of stable operation, and the fixed valve losses and higher mechanical losses in the reciprocating machine result in a falling off in efficiency at part load. The centrifugal machine has no valves and its mechanical losses are insignificant.

The pulsation or surge point is covered on pages 46 and 47 of the text by Austin H. Church and will not be repeated at this time. It is pertinent to observe that head imparted to the fluid is largely pressure head due to centrifugal force and partly velocity head. This velocity head falls off with decrease in flow until a point is reached where the fluid flows back through the machine and pressure drops to the zero flow value. The point at or near the peak of the pressure curve, where reversal occurs, is termed the surge point. This is a characteristic of centrifugal liquid pumps as well as centrifugal gas pumps.

Means of providing a wider range of stable operation before reaching this point are resorted to by centrifugal compressor engineers.

Speed reduction will provide a small measure of added stability as the pulsation point drops back as the first power of speed reduction as indicated by the slope of the indicated surge point.

Commercial approaches to providing a wider range of stable operation have resulted in the use of suction throttling and bypassing from discharge to suction or intermediate stages. You will note that the flow diagram (Fig. 18) indicates both a valve at the compressor suction that could be either manually or automatically operated and a bypass valve that could be either manually or automatically operated.

The term "commercial" was chosen because there are other methods that could be used such as a power recovery device through which by-passed air or gas would be reduced from compressor discharge to compressor suction pressure and the recovered power used to unload the main driver.

Another method that is applicable to high volume low pressure machines handling clean fluids are adjustable diffuser vanes. This method has provided a very high degree of flexibility on high volume machines for special testing purposes. Most applications of this type have been made by European firms.

Another method—adjustable inlet guide vanes—is illustrated by Clark fixed inlet guide vanes, which provide approximately 15 per cent fixed volume variation by the alternate use of radial or against rotation vanes. As will be gathered from the above percentage of 15 per cent, the method is limited in range even though arranged for automatic operation. On multi-stage units of small physical size, the method is generally confined to the first impeller which reduces its utility.

The small extent of utilization of the above three methods in the United States is possibly due to our relatively low power cost.

On high pressure machines the physical size of the equipment is not conducive to incorporation of cumbersome movable vanes and mechanisms. The fear of fouling due to foreign matter in the gas may also be a deterrent.

At the present time the economic use of centrifugals is limited to relatively high capacities, as covered hereinbefore, where steam or electrical drive fits economically.

Generally speaking, the economics of the driver, in the petroleum industry, is considered to be of greater significance than the compressor. Therefore, when burning of fuel gas direct offers the most economical power, it would appear that the centrifugal compressor will continue in a disadvantageous competitive position for some time to come.

Gas turbines, or other commercial means of providing the centrifugal with a driver that might compete with the internal combustion gas engine, are being given consideration but appear to be in the development rather than the commercial stage. ★ ★ ★

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Development of the air-cooled diesel engine*

By J. C. HOIBY, *Chief Engineer*, D. W. Onan & Sons

THROUGH the past decade there has been an increasing demand for small diesel engines of 2½ to 15 hp capacity. The sale of engines to this market has been hampered by their high cost, heavy weight, and in some instances difficult starting. Provided that there were sound, economic reasons for the use of diesel engines in small sizes, it would appear that this market would justify the development and tool-up of a modern, low-cost, diesel engine. As manufacturers of electric generating sets, the field has been viewed in that light. A study conducted to determine the economic possibilities of the diesel engine in this field revealed the following information.

A small diesel engine applied to applications where the service is short and intermittent and does not run high in total hours of yearly operation, cannot possibly equal the overall economy of a small gasoline engine. If the service of the engine is required for a considerable number of hours each day and the total hours per year are high, the application is ideal. The diesel-driven electric generating set falls into this application, as it is operated from 4 to 8 hr per day each day of the year. On this basis it is found that the advantages of the diesel engine, so far as cost is concerned, are of importance in the following order:

1. The diesel engine will run at least double the number of hours of a gasoline engine between periods of valve and combustion chamber maintenance. In these applications a small gasoline engine at constant speed suffers due to heavy deposits of lead and carbon compounds in the combustion chamber. Valve maintenance on the gasoline engine is greater due to the high exhaust valve temperature and the passage of solid lead compounds through the exhaust valve. Spark plugs and breaker points used on gasoline engines require service two to four times oftener than injectors on diesels.

2. Of secondary importance but significant, where the engine is operated a large number of hours per year, is the fuel cost. If 2000 hr per year is used as a criterion of total operation, the fuel cost of a diesel-powered generating set running at 5-kw output will require $131.40 in fuel per year. A generating set powered by a gasoline engine at this same output will require $375 in fuel per year. This is based on a cost of 9 cents per gal for the fuel oil and 15 cents per gal for the gasoline. This saving in fuel cost will approximately pay the difference in cost between the gasoline engine powered unit and a diesel-powered unit in the first year of operation. In application in foreign countries these fuel savings may be very much greater where a gallon of gasoline frequently costs several times the price of a gallon of fuel oil.

3. Aside from these economic reasons, there are special instances where the diesel engine is justified, such as high property insurance rates where the hazard of gasoline is present and where diesel fuel is already available for other engines such as are found in some marine applications.

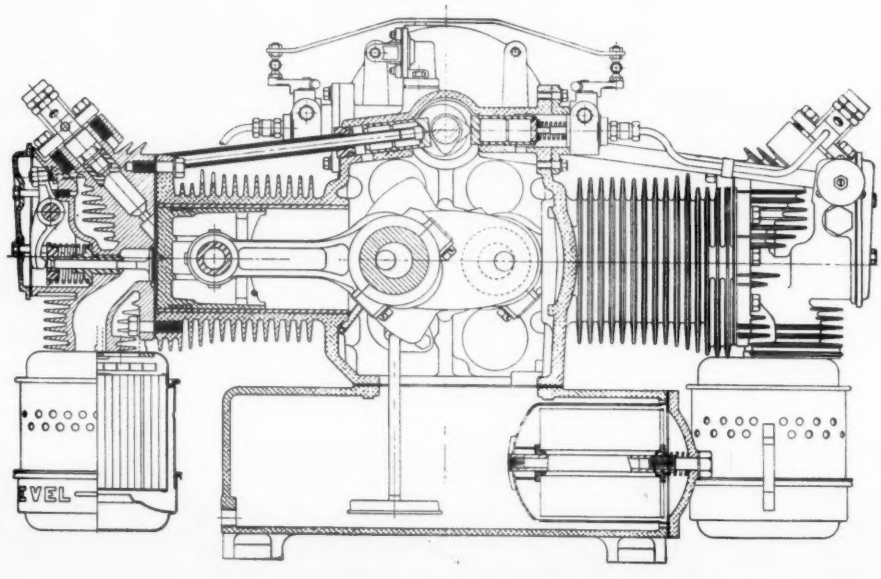
The development engineering department of D. W. Onan and Sons has been engaged for many years in the design of smaller air and water-cooled engines. In comparing both of these types there seems to be no advantage in the water-cooled type if a satisfactory cylinder wall temperature can be obtained with the air-cooled engine. Development work has, therefore, been directed to the improvement of fans, cylinder finning, foundry technique for making long, closely spaced fins and lubrication problems. As gasoline engines manufactured by Onan are the "L" head type, the most serious cooling problem is to maintain normal cylinder wall temperature adjacent to the exhaust port. The improved thermal efficiency of the diesel and the use of overhead valves simplifies this cooling problem.

To meet market requirements a two-cylinder engine of 12 hp output at 1800 rpm has been developed. The engine is of the air-cooled, opposed type, with a bore of 3½ in. and a stroke of 3½ in. This style of construction is inherently light in weight due to the short lengths of such parts as the crankshaft, camshaft, and crankcase. As the major parts of the engine are made of aluminum, this further contributes to light weight. The very short length of crankshaft lends itself to extreme rigidity and provides better distribution of loads across the face of the bearings. Better balance and a smoother running engine is obtained because the reciprocating forces from the pistons balance each other. It would appear, therefore, considering balance and rigidity of parts, that the opposed construction is the most suitable.

The engine weighs 220 lb and its dimensions are 18¾ in. high, 29¼ in. wide, and 24 in. long.

Reference to Fig. 1 shows the conventional straight-forward layout of the engine as an opposed, two-cylinder, type. The crankcase and cylinders are cast integrally of aluminum alloy. The cylinder heads are cast-iron and contain a pre-combustion chamber, and except for cooling are of a rather common type. A 17½ to 1 compression ratio is used. The prechamber volume, ratio of 55 per cent, is a little higher than normal in other engines, which is probably due to the rather short stroke of the engine. The pre-combustion chamber is formed by a sleeve that is relieved on the outside diameter to insulate it from the

FIG. 1. Sectional view showing construction of conventional two-cylinder opposed, 12 hp, air-cooled diesel.



*Presented before Society of Automotive Engineers, Tractor meeting, Milwaukee, Wisconsin, September 11 and 12, 1946.

cooler cylinder head. A pintle type nozzle is used to supply fuel to this chamber and individual high pressure injection pumps are mounted on each side of the camshaft, which prevents a symmetrical arrangement. Aluminum main and connecting rod bearings are employed and are pressure lubricated by a gear type oil pump. The aluminum main bearings are of Alcoa X-750 alloy containing 7 per cent tin. Maximum main bearing pressure is 1150 psi. Wear on these bearings appears to be less than 0.0003 in. per 1000 hr of operation. The crankshaft is a cast nickel alloy iron.

Fig. 2 is a sectional view longitudinally through the engine. It illustrates the electric starter and cooling fan arranged for use as a commercial engine. The electric starter is direct connected to the crankshaft and it performs the dual function of a motor for starting the engine and a generator for recharging the starting battery. A 12-volt starting system is used. Surrounding the generator is a rotating axial flow fan that supplies cooling air to the cylinders. The axial flow fan is used as it will supply a larger amount of air at a higher static pressure than a centrifugal type fan and its housing for a given amount of space.

In order to obtain satisfactory cooling an air volume of 550 cu ft per min is needed. This requires approximately 0.4 hp for driving the axial fan. This type of fan presents an ideal mechanical arrangement in that it performs satisfactorily with a large hub that permits mounting the starter unit inside of it. A simple drawn sheet-metal air housing is used to direct the cooling air to the cylinders. This type of housing distributes the air evenly to the cylinders and does not destroy the turbulence of the air stream, which aids the cooling. The cylinder and cylinder head heat losses are each equivalent to one-half the engine output. The exhaust gas heat loss is approximately one-third of the total energy input. It is inconvenient to provide a large fin area on the cylinder head and for this reason it is necessary that more air be directed to it than to the cylinder. The cylinder also receives cooling by the oil thrown upon it by the lubricating system and by conduction to the aluminum crankcase. The piston rings and exhaust valve temperatures are the most critical and, therefore, these parts are given the greatest attention in designing the cooling system.

Fig. 3 indicates the cylinder and head temperatures that are encountered in this engine. These temperatures, although higher than water-cooled engines, are within a satisfactory range of operation and are lower than high output aircraft engines where the cooling air pressure and velocity is much greater than is obtainable on a small stationary engine of this type. The integral construction of the cylinder and crankcase provides the effect of a finned muff around the shrunk-in cylinder liner. The use of an aluminum cylinder takes advantage of the excellent heat conductivity of this material. Longer fins are used at the outer end of the barrel to increase the cooling surface. As it is essential that ring sticking be avoided, it is necessary that the cylinder temperature be lower than the head temperature. Extra fins are provided around the injector nozzle to prevent cracking of the fuel before injection.

Figs. 4 and 5 illustrate the condition of the piston anti-thrust and thrust side, respectively, after a 500-hr run at rated output. It is to be noted that the piston is of a rather short length to diameter ratio in line with the trend of the latest diesels and aircraft engines. A thick

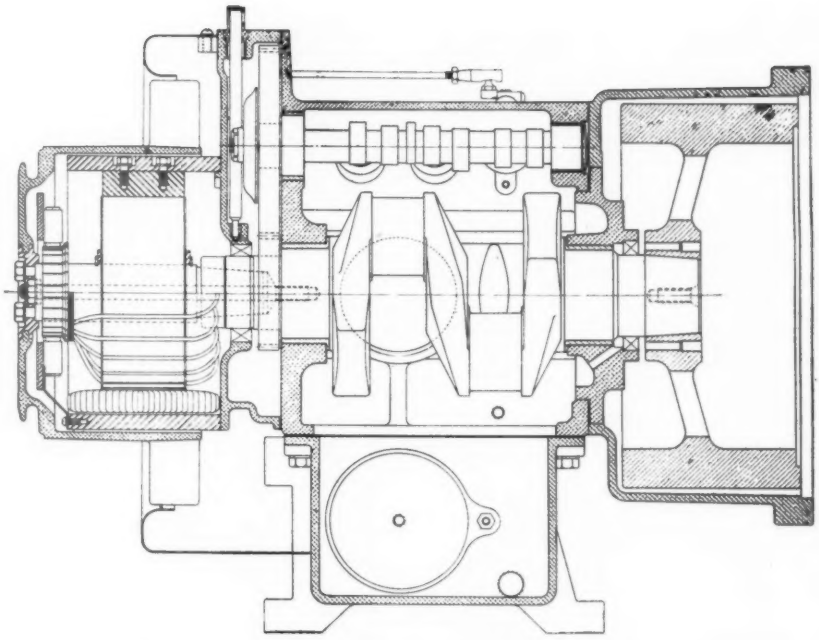


FIG. 2. Sectional view longitudinally through the engine of direct connected starter and axial flow cooling fan.

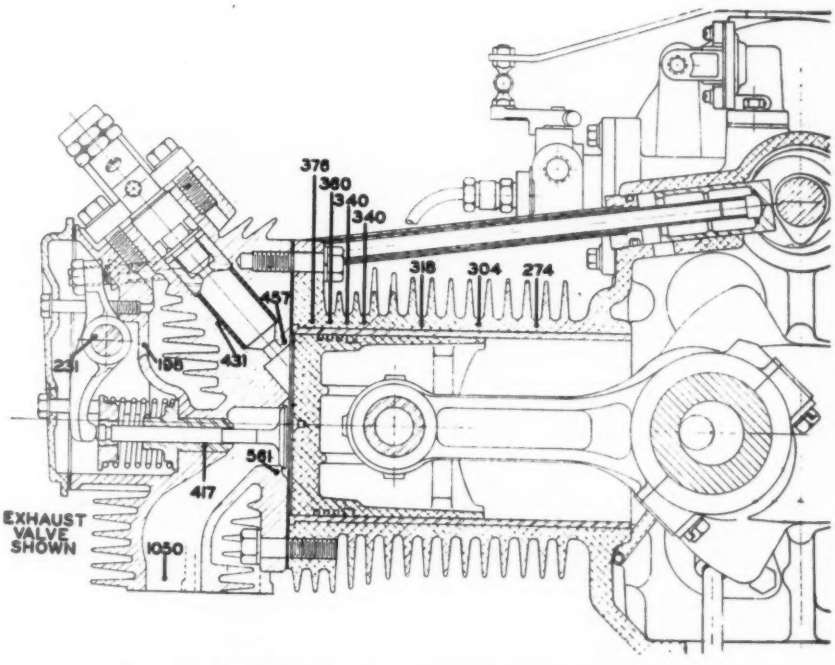


FIG. 3. Cylinder and head temperatures at rated output.

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Annually the country's installed diesel horsepower consumes 24.25 million gallons lubricating oil, at a cost of about 50 cents per gallon. The annual lube bill for diesels is therefore estimated to be about $12 million.

piston head is used that provides an even temperature distribution across its surface. There has been no evidence of excessive temperature where the blast from the combustion chamber orifice strikes the piston and there has been an absence of coked oil on the underside of the piston head. One oil control and three compression rings, and two scuff rings are provided. The bright condition of the scuff rings indicates they contact the cylinder wall and perform the function of throttling the pressure and gas temperature before it reaches the top piston ring. All rings were free in the grooves after a test run of 500 hr duration.

It has been noted during engine test work that the piston clearance bears a more important relation to ring sticking on the diesel engine than it does on a gasoline engine. In air-cooled gasoline engines it is common to fit the piston quite loosely in the cylinder. Excessive piston clearance requires a higher operating temperature so that the piston will expand and take up the clearance to transmit its heat to the cylinder wall and fins. This higher operating temperature will contribute to ring sticking. It is desirable to fit the piston with the minimum clearance that will avoid piston seizure.

Considerable attention has been given to the means of starting the engine as this is a problem on any diesel engine exposed to the wide temperature variations that occur when used in a variety of service. It is also necessary in electric generator set applications that the engine can be started by remote control circuits or in other instances automatically by turning on a light. The engine will start satisfactorily at temperatures of 40 F. At temperatures lower than this, however, additional heat is required. An electric grid type heating element is mounted as an integral part of each oil bath air cleaner, the induction air passing through the air cleaner is preheated just before entrance to the combustion chamber. On an engine of this size with a 12-volt starting system, the requirement for current to turn the engine is rather small, and with the standard batteries available a considerable amount of energy can be expended in preheating the induction air. At a cranking speed of 150 rpm the air demand of the engine is 1.46 cu ft per min. By application of 100 watts to this air the theoretical temperature rise of the air will be 200 F. Some of this heat is, of course, lost in passing through the induction port and in the cold combustion chamber; it is sufficient, however, to provide easy starting of the engine at 0 F. The electric heating elements are connected in the starting circuit of the engine and are permanently connected so that the operator need not concern himself about switching them in or out of the circuit during warm or cold weather.

A decompression solenoid is provided on each cylinder head to reduce the initial cranking torque. The solenoid plunger engages with the exhaust valve rocker arm to hold the exhaust valve open whenever the speed is less than 150 rpm. The solenoid is automatically operated by the cranking speed of the engine. It serves the additional function of stopping the engine by remote control or automatic means.

Fig. 6 illustrates the engine direct connected to an alternating current generator. In this case the exciter winding of the alternator serves as a cranking motor and a starter mounted in the fan wheel is not required. The unit is flexibly rubber mounted to avoid transmission of shock to its mounting base. A three-wire control circuit is provided for starting and stopping the engine remotely.

It is expected that there will be a future trend to the use of the air-cooled type of engine in ratings up to 30 hp due to its lower cost, lighter weight, and simplicity of manufacture. This in turn will result in the increased use of the opposed design as it lends itself especially well to air-cooling and is inherently well balanced. ★★★

FIG. 4. Anti-thrust side. FIG. 5. Thrust side of Fig. 4.
Piston condition after 500-hr run at rated output

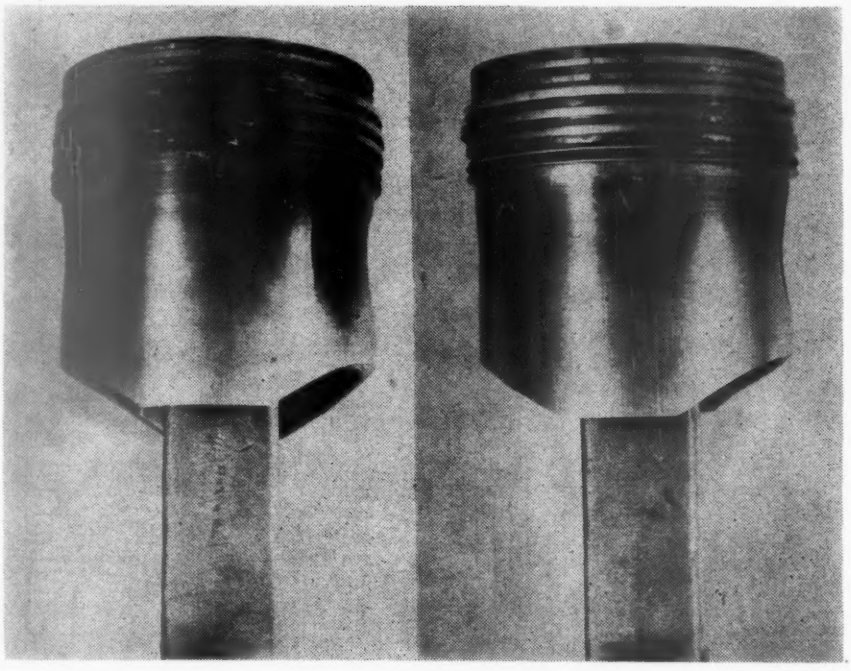
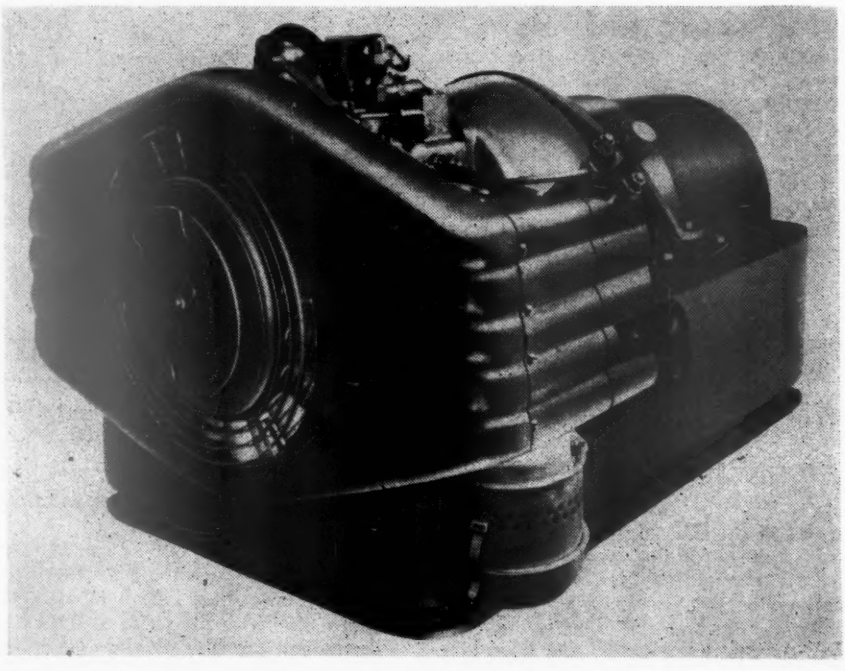
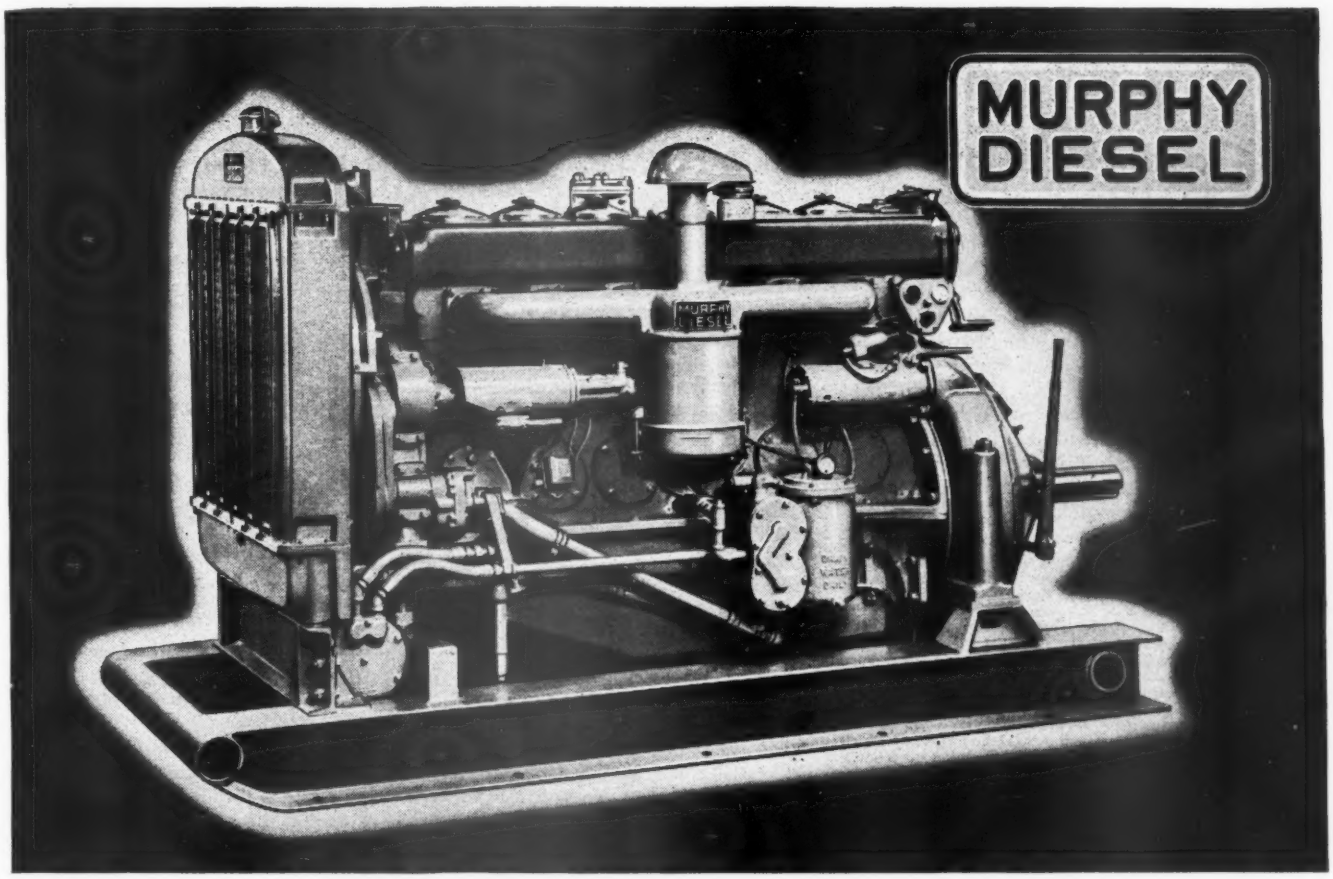


FIG. 6. Opposed engine direct connected to 5 kw electric generator.





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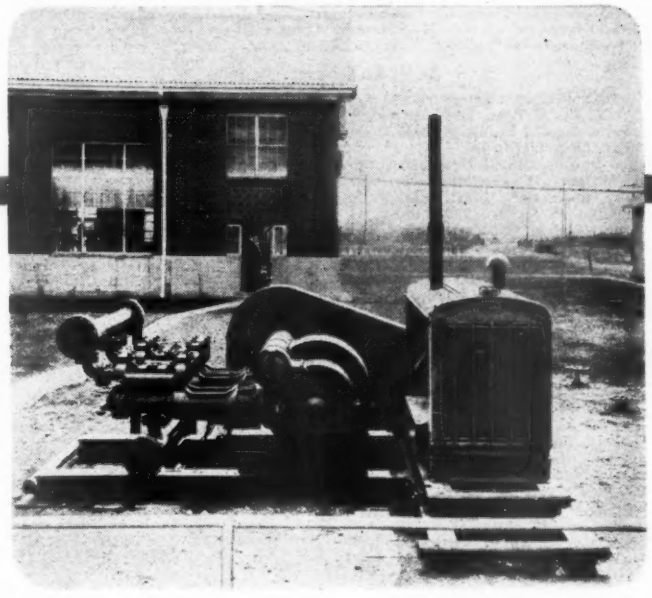

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AAODC—American Association of Oilwell Drilling Contractors.
AAPG—American Association of Petroleum Geologists.
ACS—American Chemical Society.
AGA—American Gas Association
AIME—American Institute of Mining and Metallurgical Engineers.
API—American Petroleum Institute.
ASME—American Society of Mechanical Engineers.
ASM—American Society for Metals.
ASTM—American Society for Testing Materials.
CNGA—California Natural Gasoline Association.
IIT—Illinois Institute of Technology.
IPAA—Independent Petroleum Association of America.
Oil Compact—Interstate Oil Compact Commission.
NACE—National Association of Corrosion Engineers.
NPA—National Petroleum Association.
NGAA—Natural Gasoline Association of America.
N. Tex. O&GA——North Texas Oil and Gas Association.
PEPA—Petroleum Electric Power Association.
PGCOA—Pennsylvania Grade Crude Oil Association.
Rocky Mt. O&GA—Rocky Mountain Oil and Gas Association.
SAE—Society of Automotive Engineers.
SEG—Society of Exploration Geophysicists.
SEPM—Society of Economic Paleontologists and Mineralogists.
SWGM—Southwestern Gas Measurement Short Course.
WPRA—Western Petroleum Refiners Association.

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America's Position in Europe, Manchester Boddy, *API spring meeting, Los Angeles, May 15-16, 47.*
Petroleum Industry's Public Relations Program, Don E. Gilman, *API spring meeting, Amarillo, Texas, May 22-23, 47.*
Uncontrollability Factors in Boiler Operation, Jos. A. Pelletero, *ASME, Instruments & Regulators Div., Pittsbrugh, Sept 16-18, 46.*
Positive Meter as a Flow-Rate Control Device, E. W. Jacobson, *ASME, In-Instruments & Regulators Div., Pittsburgh, Sept. 16-18, 46.*
Extension of Rotameter Theory and Its Application in New Practical Fields, Victor P. Head, *ASME, Inst & Reg Div, Pittsburgh, Sept 16-18, 46.*
Nozzle Flow Characteristics in Pneumatic Force-Balance Circuits, David B. Kirk, *ASME, Instruments & Regulators Div., Pittsburgh, Sept 16-18, 46.*
Graphic Representation and Analysis of Automatic Control Terms, J. G. Horn, *ASME, Instruments & Regulators Div., Pittsburgh, Sept 16-18, 46.*
Functional Analysis of Measurement Apparatus, H. C. Dickenson, *ASME, Instruments & Regulators Div., Pittsburgh, Sept 16-18, 46.*
Stability of Steels at Elevated Temperature, A. B. Wilder & J. D. Tyson, *ASME, New York, Dec 46.*
Lubrication Problems of Internal Combustion Engines—Today, J. Musser Miller, *ASME semi-annual meeting, June 17-20, 46.*
Fatigue Tests of Welding Elbows and Comparable Double-Mitre Bends, A. R. C. Markl, *ASME spring meeting, Tulsa, Okla., Mar 2-5, 47.*
A Method for Testing and Studying the Cost of Operation of Centrifugal Boiler Feed Pumps, A. C. Pasini and E. M. Spencer, *ASME spring meeting, Tulsa, Okla., Mar 2-5, 47.*
Oil Filter Testing, W. J. Ewbank, *ASME spring meet, Tulsa, Mar 2-5, 47.*
Fabrication Notes on Corrosion Resistant Alloys, J. C. Holmberg, *ASME spring meeting, Tulsa, Okla., Mar 2-5, 47.*
Gas Turbine Combustion, E. P. Walsh & D. W. Pouchot, *ASME spring meeting, Tulsa, Okla, Mar 2-5, 47.*
Operating Experience With Heat Pumps, Philip Sporn, *ASME spring meeting, Tulsa, Okla., Mar 2-5, 47.*
Steam Jet Refrigeration for Turbo-Generator Air, Gas & Oil Coolers, P. H. Knowlton, *ASME spring meeting, Tulsa, Okla., Mar 2-5, 47.*
Modern Filtration and Purification Methods, F. M. Steel, *ASME Nat'l Conference, Oct 7-9, 46.*
Centrifugal Purification, C. W. Bryden, *ASME Nat'l Conference, Oct 7-9, 46.*
Gravity and Pressure Oil Filters, Their Uses and Applications, E. M. May, *ASME, Nat'l Conference, Oct 7-9, 46.*
Low Temperature Impact Properties of Some Cast Steels, H. D. Churchill, *ASME Nat'l Conference, Oct 7-9, 46.*
Turbines for Natural-Gas Expansion, Stephen Bencze, *ASME Nat'l Conference, Oct 7-9, 46.*
Motion and Time Study Application to Petroleum Production, H. G. Thuesen, *ASME Nat'l Conference, Oct 7-9, 46.*
Cavitation in Pumps, B. R. Walsh, *ASME Nat'l Conference, Oct 7-9, 46.*
Visual Demonstration of Cavitation as Viewed by Stroboscope, B. R. Walsh, *ASME Nat'l Conference, Oct 7-9, 46.*
New Developments in Compressors for Petroleum Industry Applications, J. N. Mackendrick, *ASME Nat'l Conference, Oct 7-9, 46.*
A Study of the Corrosion of Copper Alloy Condenser Tubes, N. W. Mitchell, *ASME Nat'l Conference, Oct 7-9, 46.*
Heat Exchanger Design, D. E. Fields, *ASME Nat'l Conference, Tulsa, Okla., Oct 7-9, 46.*
Tube Rolling Study, M. Q. Colton, *ASME Nat'l Conference, Tulsa, Okla., ASME Nat'l Conference, Oct 7-9, 46.*
Use of Stellite and Other High Alloyed Materials to Combat Corrosion and Abrasion in the Petroleum Industry, C. G. Chisholm, *ASME Nat'l Conference, Tulsa, Okla., Oct 7-9, 46.*
Wear Resistance of Gray Irons, F. G. Sefing, *ASME Nat'l Conference, Tulsa, Okla., Oct 7-9, 46.*
Relief Valves, Their Function & Maintenance, John Gieseke, *ASME Nat'l Conference, Tulsa, Okla, Oct 7-9, 46.*
Desirable Characteristics of Coating Liquids for Rotating Screen & Panel Type Air Filters, G. E. Cunningham, *ASME Nat'l Conference, Tulsa, Okla., Oct 7-9, 46.*
Notched Bar Impact Properties of Some Nickel Steels After One Year Exposure to Liquid Nitrogen, T. N. Armstrong & A. J. Miller, *ASME Nat'l Conference, Tulsa, Okla., Oct 7-9, '46.*
Some Notes on the Use of Free Machining Steels in Connection With Petroleum Equipment, M. E. Holmberg & F. Prange, *ASME Nat'l Conference, Tulsa, Okla., Oct 7-9, 46.*

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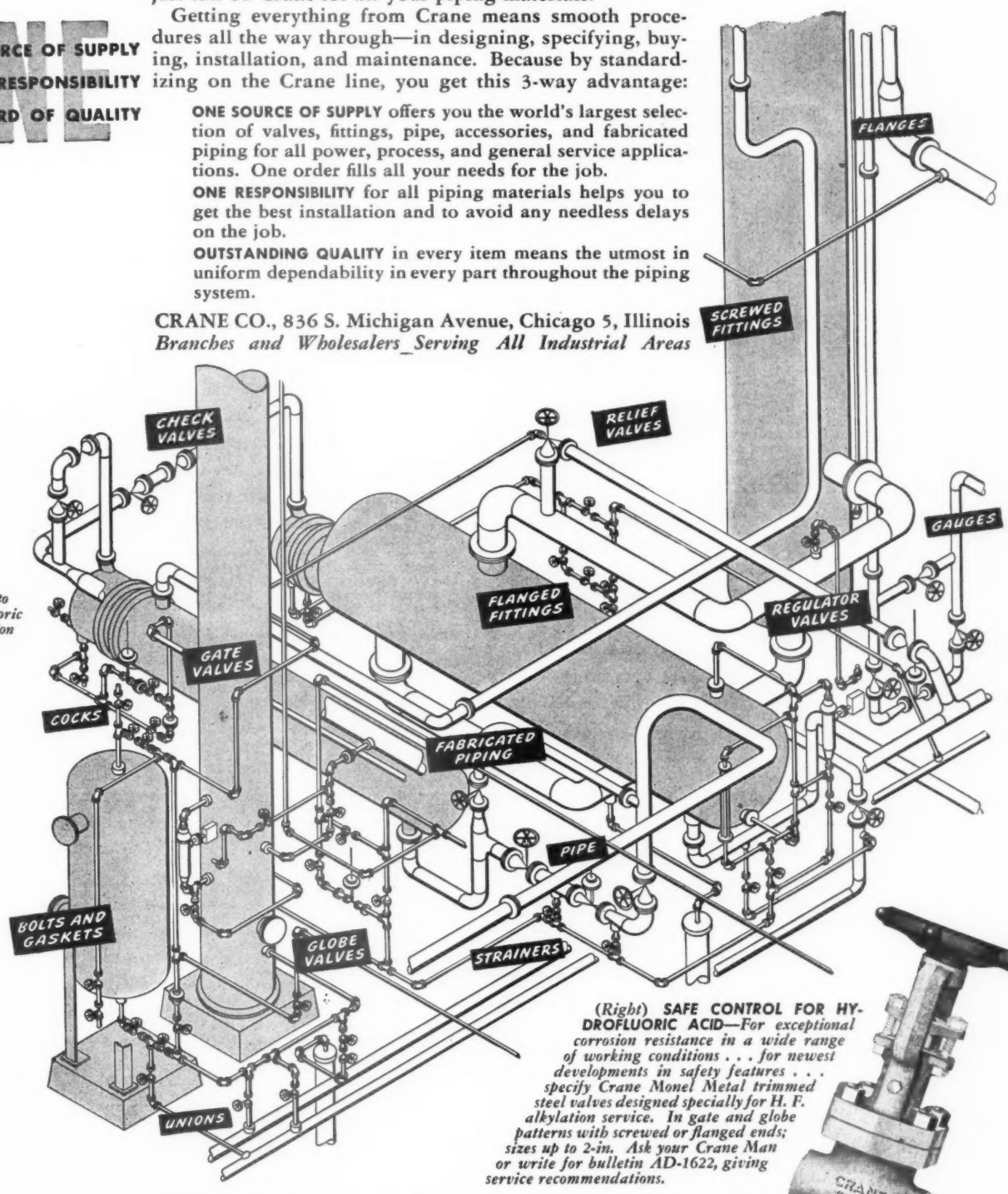

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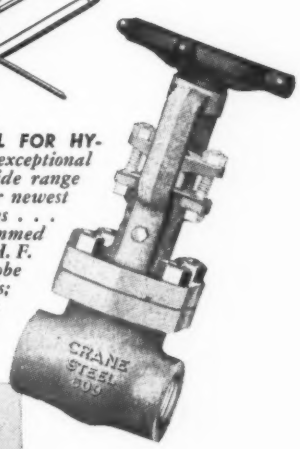

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Combating Fatigue Failures, J. O. Almen, *ASM Congress & Exposition, Oakland, Calif., March 24-27, 47.*
Recent Developments in Magnesium Alloys, Dr. J. C. MacDonald, *ASM Congress & Exposition, Oakland, Calif., March 24-27, 47.*
Corrosion of Metals, Dr. R. J. McKay, *ASM Congress & Exposition, Oakland, Calif., March 24-27, 47.*
Protective Coatings, R. M. Burns, *ASM Congress & Exposition, Oakland, Calif., March 24-27, 47.*
Method for Predicting Failure of Metals, P. E. Cavanagh, *ASTM annual meeting, Buffalo, N. Y., June 46.*
Increasing Diesel Horsepower vs. Diesel Fuel Supply, Robert H. Morse, Jr., *ASTM Forum, Chicago, Nov 13, 46.*
Diesel Engine and Burner Distillate Fuels, John C. Day, *ASTM Forum, Chicago, Nov 13, 46.*
Report of Committee D2 on Petroleum Products and Lubricants, *ASTM Forum, Mar 47.*
New Type of Magnetic Flaw Detector, Carlton H. Hastings, *ASTM Forum, Mar 47.*
Diesel Developments of Significance, C. G. A. Rosen, *IIT Midwest Powers Conf., Chicago, Apr 47.*
Latest Developments in Electronic Control, W. D. Cockrell, *IIT Midwest Powers Conf., Chicago, Apr 47.*
Recent Gas Turbine Developments at Brown Boveri, Paul R. Sidler, *IIT Midwest Powers Conf., Chicago, Apr 47.*
Effect of War on Our Domestic Petroleum Reserves, James V. Brown, *IPAA annual meeting, Fort Worth, Texas, Oct 28-30, 46.*
Effective Cooperation of Associations of Oil and Gas Producers, H. B. Fell, *IPAA annual meeting, Fort Worth, Texas, Oct 28-30, 46.*
Management's Stake in Freedom, Edwin Venard, *IPAA annual meeting, Fort Worth, Texas, Oct 28-30, 46.*
Military Viewpoint on Petroleum Supply, Col. G. H. Vogel, *IPAA annual meeting, Fort Worth, Texas, Oct 28-30, 46.*
Oxidation—Resistant Alloys, Benjamin Lustman, *IPAA annual meeting, Fort Worth, Oct 28-30, 46.*
Known and Potential Sources of Supply of Petroleum in the U. S., James V. Howell, *IPAA annual meeting, Fort Worth, Texas, Oct 28-30, 46.*
Intrinsic Value of Natural Gas—A National Asset, Dr. Frank H. Dotterweich, *IPAA annual meeting, Fort Worth, Texas, Oct 28-30, 46.*
Worldwide Petroleum Supply and Demand, H. W. Page, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
History of Oil Development in Southeastern States, Clyde Alexander, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Reserves, Availability and Conservation of Oil & Gas in the Southeastern States, Alec Crowell, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Economic Value Oil and Gas to Mississippi, E. D. Kenna, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Elements of a Sound National Oil & Gas Policy, Senator Jos. C. O'Mahoney, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Oil Industry Public Relations, Keeton Arnett, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Proposed Amendment to the Natural Gas Act, Russell B. Brown, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Current Problems of the Natural Gas Industry, N. C. McGowan, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Oil and Reciprocal Trade Agreements, Dr. John Lee Coulter, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Foreign Oil Trends and the Domestic Petroleum Industry, Minor S. Jameson, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Import Policy Is Part of National Oil & Gas Policy, Harold B. Fell, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Foreign Oil—Developments, Operations, & Supply, L. F. McCollum, *IPAA midyear meeting, Jackson, Miss, May 8-9, 47.*
Forecast for Oil in 1947, Ernest O. Thompson, *Oil Compact winter meeting, Dallas, Texas, Dec 46.*
Oil and Gas Conservation as an Incentive for Development, Gov. Beauford H. Jester, *Oil Compact, Birmingham, Ala, Apr 25, 47.*
An Experiment in the Underground Gasification of Coal at the Gorgas Mine of Alabama Power Co., Milton H. Fies, *Oil Compact, Birmingham, Ala., Apr 25, 47.*
Use of Inhibitors in Corrosion Control, Norman Hackerman, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Oxidation of Stainless Alloys, James T. Gow, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Thermogalvanic Corrosion, R. M. Buffington, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Non-Destructive Methods of Determining Metal Plate Thickness, J. G. Kerley (B. G. Crane), *NACE annual meeting, Chicago, Apr 7-10, 47.*
Guide to Selecting Corrosion-Resistant Materials, L. G. Vande Bogart, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Aluminum Galvanic Anodes: Pt. 1, R. A. Hoxeng & R. H. Brown; Pt. 2, Ellis Verink, R. A. Hoxeng & R. H. Brown, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Silicates for Corrosion Inhibition in the Oil Industry, Alan C. Nelson, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Effect of Carbide Structure on Corrosion Resistance of Steel, R. W. Manuel, *NACE annual meeting, Chicago, Apr 7-10, 47.*
A Challenge to the Corrosion Engineer, H. H. Anderson, *NACE annual meeting, Chicago, Apr 7-10, 47.*
On the Other Side of the Fence, Tom L. Holcombe, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Corrosion Problems in Communications and Radio Equipment Design, L. P. Morris, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Salt as a Medium of Corrosion of Underground Cables, A. G. Andrews, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Attenuation of Drainage Effects on a Long Uniform Structure With Distributed Drainage, J. M. Standring, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Electrochemical Factors in Underground Corrosion of Lead Cable Sheath, V. G. Albano, *NACE annual meeting, Chicago, Apr 7-10, 47.*
Progress Report on Lubricants Projects in A.S.T.M., J. C. Geniesse, *NPA annual meeting, Atlanctic City, N. J., Sept 18, 46.*
Social and Economic Values Arising from Widespread, Abundant Availability of Petroleum Products, John D. Gill, *NPA annual meeting, Atlantic City, N. J., Sept 18, 46.*
Collective Bargaining Contracts in the Petroleum Industry, B. L. Stilphen & Jos. L. Miller, *NPA annual meeting, Atlantic City, N. J., Sept 18, 46.*
New Times and Old Problems, Gen. B. H. Markham, *NPA annual meeting, Atlantic City, N. J., Sept 18, 46.*
Activities of the Oil & Gas Division, Max W. Ball, *NPA semiannual meeting, Cleveland, Ohio, Apr 17-18, 47.*
Public Opinion and the Future of the Oil Business, Jake L. Hamon, *NGAA annual meeting, Dallas, Texas, Apr 17-19, 47.*
Newer Electric Power Equipment for the Oil Industry, B. N. Brown, *PEPA annual meeting, Tulsa, Okla., Dec 3-4, 46.*
Trends in the Consumption and Quality Characteristics of the Petroleum Fuels, Wm. M. Holaday R. E. Albright, T. L. Apjohn, E. F. Miller, *NGAA annual meeting, Dallas, Texas, Apr 17-19, 47.*
Legislative Problems, by States, Facing the Oil Industry, (H. H. Healey, Chairman, Legal & Legislative Committee), *Rocky Mt. O&G annual meeting, Denver, Colo., Nov 21-23, 46.*
How Economics of the Oil Industry Affect the Economics of the Country, Capt. A. A. Nicholson, *Rocky Mt. O&G annual meeting, Denver, Colo., Nov. 21-23, 46.*
Development of the Air-Cooled Diesel Engine, J. C. Hoiby, *SAE annual meeting, Denver, Colo., Nov 21-23, 46.*
Large Capacity Displacement Meters, A. F. Benson, *SWGM short course, Norman, Okla., May 6-8, 47.*
Pressure Boosting Regulators for High and Intermediate Pressure Systems, W. O. Jones, *SWGM short course, Norman, Okla., May 6-8, 47.*
Problems in Gas Measurement at Extremely High Pressures, K. C. Reed & Paul Cunningham, *SWGM short course, Norman, Okla., May 6-8, 47.*
Operation and Maintenance of Orifice Meters, A. H. Hathaway, *SWGM short course, Norman, Okla., May 6-8, 47.*
Gas Accounting—Wet Gas, K. R. Tibbetts, *SWGM short course, Norman, Okla., May 6-8, 47.*
Operation of Flow Calorimeter, L. S. Reid, *SWGM short course, Norman, Oklahoma, May 6-8, 47.*
Orifice Meters, J. L. Cottrell, *SWGM short course, Norman, Okla., May 6-8, 1947.*
Methods of Pilot Loading Regulators, G. Blanchard Smith, *SWGM short course, Norman, Okla., May 6-8, 47.*
Calculation of Meter Charts, R. W. Howard, *SWGM short course, Norman, Okla., May 6-8, 47.*
Recording Instruments, J. F. Bailey, *SWGM short course, Norman, Okla., May 6-8, 47.*
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Practical Meter and Regulator Station Design, Pat H. Miller, *SWGM short course, May 6-8, 47.*
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Gas Regulation and Blending, A. J. Hanssen, *SWGM short course, Norman, Okla., May 6-8, 47.*
100 Years of Public Relations for Oil, Ralph C. Champlin, *WPRA annual meeting, San Antonio, Texas, Mar 24-26, 47.*
Petroleum and Natural Gas—Uses and Possible Replacements, R. E. Wilson & J. K. Roberts, *WPRA annual meeting, San Antonio, Mar 24-26, 47.*
Copper Strip Corrosion Tests, John A. Bolt, *Standard Oil Co. (Ind) joint technical meeting, French Lick, Ind., May 5-9, 47.*
Dual Fuel Engine, Gordon Lefebvre, *American Public Power Assn., Cleveland, Ohio, May 22, 47.*
Economic Potentialities and Problems for the Post-Reconversion Period, Murray Shields, *Controllers' Congress, Chicago, Ill., June 19, 46.*
Development of Natural Resources the Contribution of the Petroleum Industry to Resource Administration, Joseph E. Pogue, *Princeton University Bicentennial, Oct 2, 46.*
Significance of Petroleum in a Modern World, Dr. Gustav Egloff, *Science Forum Gen'l Electric Co., Sta. WGY, Schenectady, N. Y., April 23, 47.*

Application of L-P Gas Plants to the Gas Utility Problems, Warren C. Meyer, *Gas Meters Assn. of Florida-Georgia, Boca Raton, Fla., Apr 26, 47.*
Adequacy of Domestic Petroleum Supply, H. H. Hill, *U. S. Chamber of Commerce annual meeting, May 1, 47.*
Effect of Imports on the Domestic Petroleum Supply, Merle Becker, *U. S. Chamber of Commerce annual meeting, May 1, 47.*
Challenge We Face in Peacetime, W. S. Hallanan, *PGCOA, Pittsburgh, Penn., June 5, 47.*

EXPLORATION AND PROSPECTING

Review of Geophysical Prospecting Methods, Devices and Procedures, C. H. Dresbach & Paul Weaver, *AIME, Galveston, Texas, meeting, Oct. 3-5, 46.*
Geothermal Gradients in Mid-Continent and Gulf Coast Oil Fields, Earl A. Nichols, *AIME, Galveston, Texas, meeting, Oct. 3-5, 46.*
Pseudo Shoreline of the Repetto Formation, Manley L. Natland, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Submarine Geology of Southern California, Kenneth O. Emery, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Whither Exploration, J. J. Jakosky, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Environmental Condition During Deposition of Several Formations in the Ancient Gulf of Mexico, F. W. Rolshausen, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Geological Masks and Prejudices, E. B. Noble, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Highlights of Domestic Developments in 1946, K. C. Heald, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Highlights of Foreign Development in 1946, L. G. Weeks, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Paleogeoligic Setting for Oil Accumulation in California, Harold W. Hoots, *AAPG, annual meeting Los Angeles, Mar. 24-27, 47.*
Origin and Evolution of the Los Angeles Basin, H. L. Driver, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Geologic Development of the Ventura Basin and Its Petroleum Deposits, Thomas L. Bailey, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Genesis and Evolution Through the Tertiary of the Interior Valley Basin of Calif., Glenn C. Ferguson, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Oil and Gas Prospects of Washington & Oregon, Hampton Smith, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
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Geologic Framework of the Pacific Region, Walter H. Bucher, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Geological Sketch of the Japanese Islands, Chas. W. Chesterman, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Petroleum Production & Resources of Japan, David Cerkel & J. L. Williams, *AAPG, annual meeting, Los Angeles, Mar. 24-27, 47.*
Seismic Exploration in Sumatra, O. F. Van Beveren, *AAPG, annual meeting, Mar. 24-27, 47.*
Subsurface Exploration of Bikini Atoll by the Seismic Refraction Method, Milton B. Dobrin & Beauregard Perkins, Jr., *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Structural Types and Trends in South China, Peter Misch, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Outline of the Geological History of New Zealand in the Light of Recent Contribution, Francis J. Turner, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Stratigraphic Sequence in the Philippines, Robt. M. Kleinpell, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
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Central America as a Petroliferous Province, W. P. Woodring, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Cyclic Sedimentation in Paleozoic Rocks Along the Alcan Highway in Northern British Columbia, Lowell R. Laudon & B. J. Chronic, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Exploration and Evaluation of Petroleum Possibilities in Southwestern Alaska, Lewis B. Kellum, *AAPG annual meet, Los Angeles, Mar 24-27, 47.*
Petroleum Geology of Eastern Peru & Ecuador, Bernard Kummel, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Petroleum Geology in Chile, Glen M. Ruby, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Overthrust Structure of the Alberta Foothills, Canada, Theodore A. Link, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Thrust Faulting in the Ventura Basin, Calif., Edw. C. H. Lammers, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Montana & Wyoming Examples of Overthrusting in Relation to Petroleum Accumulation, D. L. Blackstone, Jr., *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Geology of Basement Comples, Edison Field, Calif., John H. Beach, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Exploratory Drilling in 1946, F. H. Lahee, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Kraft-Prusa Field, Central Kansas, Robt. F. Walters & Arthur S. Price, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Apco Field, Pecos County, Texas, Samuel P. Ellison, Jr., *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Cumberland Oil Field, Bryan & Marshall Counties, Okla., Ira H. Cram, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Oregon Basin Oil & Gas Field, Wyoming, Paul T. Walton, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Elk Basin Field, W. S. McCabe, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Keystone Field, Winkler Co., Texas, Karl A. Mygdal, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
TXL Field, Ector Co., Texas, C. D. Cantrell, Jr., *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Relation of Clay Mineralogy to the Origin & Recovery of Petroleum, Ralph E. Grim, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Rangely Oil Field, Rio Blanco Co., Colo., W. Y. Pickering & C. L. Dorn, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Historical Mechanics of Clinton Sand Deposition, James F. Swain, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Geology of West Tepetate Oil Field, Jefferson Davis Parish, La., Fred W. Bates & Jay B. Wharton, Jr., *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
Tinsley Field, Yazoo Co., Miss., F. R. Schroeder, *AAPG annual meeting, Los Angeles, Mar 24-27, 47.*
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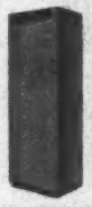

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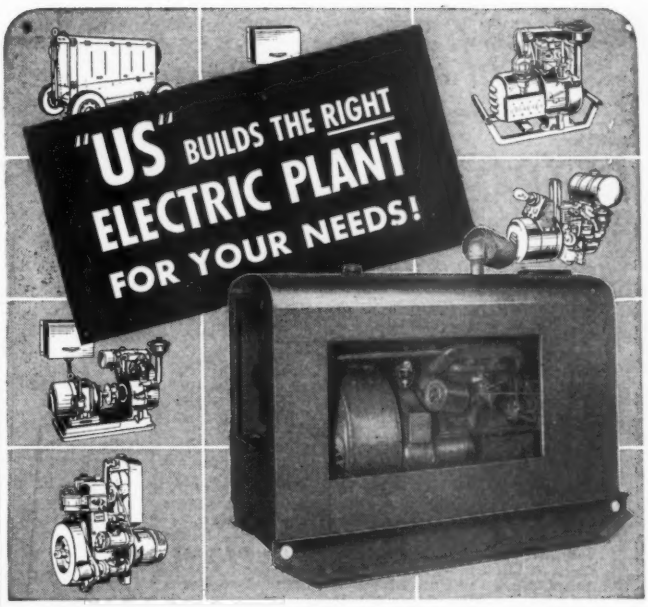

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Extending the Application of Electric Analogy in Oil Reservoir Studies, Henry Schaefer, *AIME, Galveston, Texas, Oct 3-5, 46.*

Use of Plastics in Consolidating Loose Sands in Wells, R. H. Smith & C. Polk, Jr., *AIME, Galveston, Texas, Oct 3-5, 46.*

Use of Helium as a Tracer in Oil and Gas Fields, E. M. Frost, Jr., *AIME, Galveston, Texas, Oct 3-5, 46.*

Evaluation of Pressure Maintenance by Internal Gas Injection in Volumetrically Controlled Reservoirs, E. Chas. Patton, Jr., *AIME, Galveston, Texas, Oct 3-5, 46.*

Study of Some Factors Affecting Gun Perforating, S. C. Oliphant & R. Floyd Farris, *AIME, Galveston, Texas, Oct 3-5, 46.*

Interstitial Water by the Capillary Pressure Method, O. F. Thornton & D. L. Marshall, *AIME, Galveston, Texas, Oct 3-5, 46.*

Calculated Recovries by Cycling From a Retrograde Reservoir of Variable Permeability, M. B. Standing, E. N. Lindblud & R. L. Parsons, *AIME, Pet. Div., Los Angeles, Oct 24-25, 46.*

Some Theoretical Aspects of Well Drainage and Economic Ultimate Recovery, Vaughn Moyer, *AIME, Pet. Div., Los Angeles, Oct 24-25, 46.*

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Volumetric Behavior of Oil & Gas From Several San Joaquin Valley Fields, B. H. Sage & R. H. Olds, *AIME, Pet. Div., Los Angeles, Oct 24-25, 46.*

Gas Conservation in West Texas, D. V. Carter, *AIME, Austin, Tex., Dec 46.*

Reservoir Study of the West Edmond Hunton Pool, Okla., Dr. Max Littlefield, L. O. Gray, A. C. Godbold, *AIME, Austin, Texas, Dec 46.*

Reservoir Study of the West Edmond Hunton Pool, Okla., Dr. Max Littlefield, *AIME annual meeting, New York, Mar 17-22, 47.*

Quantitative Valuation of Methods of Procedure in Water-Flood Oil Production, Harry M. Ryder, *AIME annual meeting, New York, Mar 17-22, 47.*

Phase Behavior in the Methane-Ethane-n-Pentane System, G. W. Billman, B. H. Sage & W. N. Lacey, *AIME annual meeting, New York, Mar 17-22, 47.*

Calculated Effect of Pressure Maintenance on Oil Recovery, Robt L. Hoss, *AIME annual meeting, New York, Mar 17-22, 47.*

Meter for Measuring the Distribution of Gas Flow in Well Bores (synopsis), F. Morgan, D. W. Reed & L. L. Gray, *AIME annual meeting, New York, Mar 17-22, 47.*

Well Flowmeter for Logging Producing Ability of Gas Sands, R. P. Vincent, R. M. Leibrock & C. W. Ziemer, *AIME annual meeting, New York, Mar 17-22, 47.*

Potentiometric Model Studies, B. D. Lee, *AIME annual meetisg, New York Mar 17-22, 47.*

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Advantages of Brines in Secondary Recovery of Petroleum by Water-Flooding, Richard V. Hughes, *AIME, Texas Sec., Wichita Falls, Mar 1, 46, & Pittsburgh, Pa., Nov 8, 46.*

Calculated Effect of Pressure Maintenance on Oil Recovery From a Solution Gas Drive Reservoir, Robt. L. Hoss, *AIME joint section meeting, Austin, Texas, Dec 18-19, 46.*

Salt Water Injection and Pressure Maintenance E. Texas Field, Winfield S. Morris, *AIME joint section meeting, Austin, Texas, Dec 18-19, 46.*

Material Balance Method of Evaluating Pressure-Maintenace by Internal Gas-Injection in Tight. Volumetrically Controlled Reservoirs, E. Chas. Patton, Jr., *AIME, Galveston, Texas, Oct 3-5, 46.*

Marble Shooting, J. Gordon Buch, *API spring meeting, Pittsburgh, June 13-14, 46.*

Design and Construction of Water Pumping Plants, George W. Holbrook, *API spring meeting, Pittsburgh, June 13-14, 46.*

Gas Recovery Systems, Douglas Rogers, Jr., *API spring meeting, Pittsburgh, June 13-14, 46.*

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Practical Considerations in Evaluating Pressure Maintenance, Lloyd L. Gray, *API spring meeting, Okla. City, June 6-7, 46.*

Problems of Unitization, R. M. Williams, *API spring meeting, Okla. City, June 6-7, 46.*

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Pumping-Equipment Selection for Secondary-Recovery Developments, E. N. Kemler, *API annual meeting, Chicago, Nov 14, 46.*

Homogeneous Permeability Determination, S. T. Yuster, *API annual meeting, Chicago, Nov 14, 46.*

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Case History of Water Flooding in Throckmorton Co., Texas, Paul C. Dean, *API spring meeting, Fort Worth, Tex., Mar 27-28, 47.*

Packer Problems in West Texas, T. H. Dwyer, *API spring meeting, Fort Worth, Texas, Mar 27-28, 47.*

Inventory of Gas Drive Operations in North Texas, West Texas and New Mexico Pt. 1, North Texas, L. F. Peterson; Pt. 2, Texas & N. Mex., Lee Flood, *API spring meeting, Fort Worth, Texas, Mar 27-28, 47.*

Water-Flooding Is Essential, David Scott, Jr., *API spring meeting, Pittsburgh, Apr 16-18, 47.*

Effects of Increase in Water Pressure on Water-Flooding Oil Productios, Harry M. Ryder, *API spring meeting, Pittsburgh, Apr 16-18, 47.*

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Effect of Properties of Flood Water on Rate of Input & Oil Production, K. H. Andresen & E. T. Heck, *API annual meeting, Chicago, Nov 11-14, 46.*

Input-Well Equipment, Geo. W. Holbrook & W. H. Young, Jr., *API annual meeting, Chicago, Nov 11-14, 46.*

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Restored State Method for Determination of Oil in Place and Connate Water, W. A. Bruce & H. J. Welge, *API district meeting, Amarillo, Texas, May 22-23, 47.*

Productivity of Individual Pay Zones Used for Determining Completion Efficiencies—Hugoton Field, Kans., R. B. LeFever & Henry Schaefer, *API district meeting, Amarillo, Texas, May 22-23, 47.*

General Pressure-Volume-Temperature Correlation for Mixtures of California Oil and Gases, M. B. Standing, *API spring meeting, Los Angeles, May 15-16, 47.*

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Results of Experimental Water Flooding in the Haynesville Field, Pettit Zone, A Lime Reservoir Originally Under Dissolved Gas Drive, O. S. Ervub, *API spring meeting, Amarillo, Texas, May 22-23, 47.*

Principles of Quantitative Gas Analysis and Testing, A. W. Gauger, *ASME, Instruments & Regulators Div., Pittsburgh, Sept 16-18, 46.*

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National Stripper Well Survey, 1945. E. G. Dahlgren, *Oil Compact, Winter Meeting, Dallas, Texas, Dec 46.*

Plan for Increasing the Recovery of Oil in Texas, Paul D. Torrey, *N. Tex. O&GA, Wichita Falls, Mar 8, 47.*

Results of Water-Flooding Oil Sands in No. & No. Central Texas, D. B. Taliaferro & R. K. Guthrie, *N. Tex. O&GA, Wichita Falls, Mar 8, 47.*

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My Experience With Water Flooding in North Texas, H. M. McClain, *N. Tex. O&GA, Wichita Falls, Mar 8, 47.*

Selective Plugging, Don Martin, *N. Tex. O&GA, Wichita Falls, Mar 8, 47.*

Electrification on Producing Oil Fields, J. N. Poore, *PEPA annual meeting, Tulsa, Okla., Dec 3-4, 46.*

Field Testing and Maintenance of Large Capacity Displacement Meters, R. F. Nowlin, *SWGM short course, Norman, Okla., May 6-8, 47.*

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Problems in Measurement of Natural Gas Containing Hydrogen Sulphide, Round Table Discussion, led by L. L. Jordan, *SWGM short course, Norman, Okla., May 6-8, 47.*

REFINING

Mechanism of Catalytic Cracking, R. C. Hansford, *ACS, Pet. Div. 25th Anniversary, Chicago, Sept 10, 46.*

Improved Method for Determining the Olefin Content of Gasoline, G. R. Bond, Jr., *ACS, Pet. Div. 25th Anniversary, Chicago, Sept 10, 46.*

Experimental Equilibrium Constants for the Isomeric Hexanes, B. L. Evering & E. L. d'Ouville, *ACS, Pet. Div. 25th Anniversary, Chicago, Sept 10, 46.*

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Chemical Refining of Aromatic Hydrocarbons From Petroleum, P. L. Brandt, R. J. Lee, F. T. Wadsworth, *ACS, Pet. Div. 25th Anniversary, Chicago, Sept. 10, 46.*

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Petroleum, 1921 to 1971, Bruce K. Brown, *ACS, Pet. Div. 25th Anniversary, Chicago, Sept. 10, 46.*

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Relative Reactivity of Allylic Chlorides, Lewis F. Hatch, Leon B. Gorden & John J. Russ, *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

Removal of Acidic Constituents in Hydrocarbon Solutions by Absorption on Silica Gel, D. A. Shock & Norman Hackerman, *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

Effect of Altitude on C_4 and C_5 Blending Calculation, N. B. Haskell & J. A. Rediner, *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

Studies on the Activation of and Adsorption on Carbon Black, Norman Hackerman & A. L. McClellan, *ACS, regional meeting, Dallas, Texas, Dec 12-13, 46.*

Sample Entering System for Mass Spectrometric Analysis—Mass Spectra of Ten Aromatic Hydrocarbons, S. E. J. Johnsen, *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

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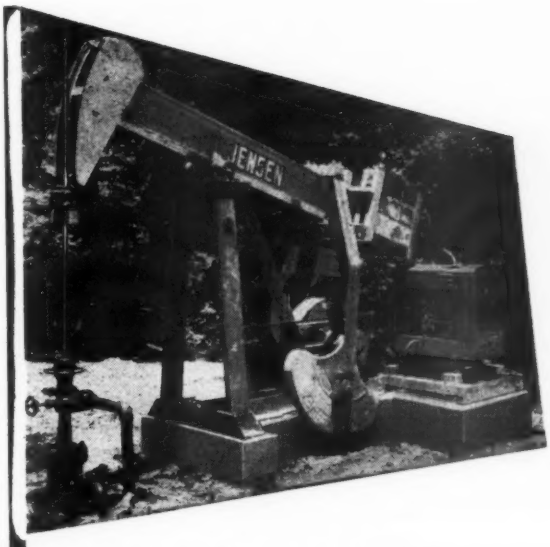

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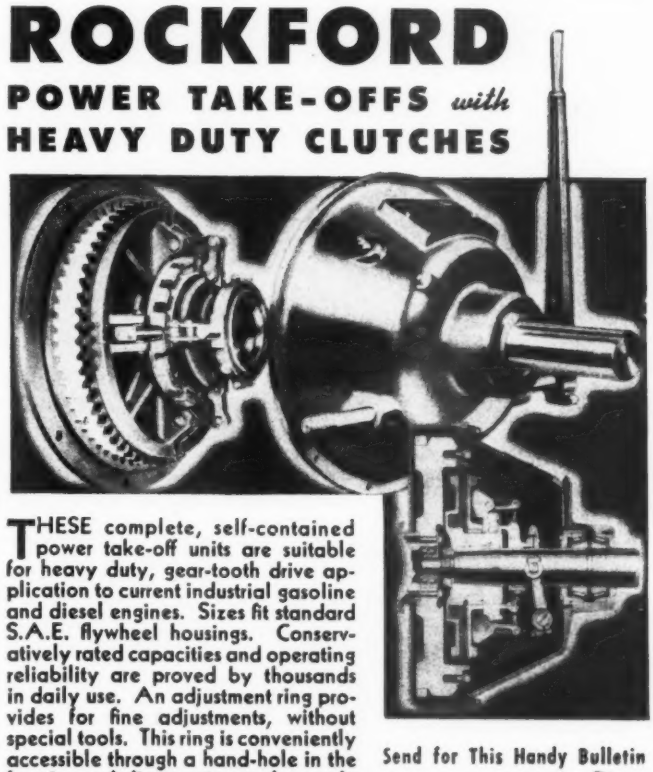

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Method for the Determination of Optimum Conditions for Titrimetric Determinations, Wm. B. Huckabay & Clyde J. Newton, *ACS regional meeting, Dallas, Texas, Dec. 12-13, 46.*

Method for the Determination of Optimum Conditions for Titrimetric Determinations—II The Determination of Acetone, Wm. B. Huckabay, Clyde J. Newton & A. V. Metler, *ACS region. meet., Dallas, Dec 12-13, 46.*

Commercial Application of Petroleum Naphthas, H. N. Frost & C. A. Murray, *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

History of Commercial Production of Butadiene by the Catalytic Dehydrogeneration of Butylenes, W. L. Hiller, Jr., *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

Catalyst Analysis for Catalytic Cracking of Petroleum, A. R. Rescorla, *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

Studies of Laboratory Low Temperature Fractional Distillation-Optimum Charging Rates, C. E. Starr, Jr., J. S. Anderson & V. M. Davidson, *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

Flow Properties of Asphalt Emulsions, D. V. Lyttleton & R. N. Traxler, *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

Effect of the Variables on the Alkylation of Isobutane With Ethylene in the Presence of Aluminum Bromides, L. G. Sharp, *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

Phase Behavior in the Methane-ethane-n-pentane System, W. N. Lacey, G. W. Billman & B. H. Sage, *AIME annual meeting, New York, Mar 17-22, 47.*

Naphtha Polyforming, W. C. Offutt, P. Ostergaard, M. C. Rogle & H. Beuther, *API annual meeting, Chicago, Nov. 14, 46.*

Naphtha Polyforming With Outside Gas, W. C. Offutt, P. Ostergaard, M. C. Fogle & H Beuther, *API annual meeting, Chicago, Nov 14, 46.*

Miscellaneous Fractionating Techniques, J. J. Cicalese, J. A. Davies, P. J. Harrington, G. S. Houghland, A. L. J. Hutchinson & T. J. Walsh, *API annual meeting, Chicago, Nov 14, 46.*

Analysis of Alkylates & Hydrocodimers, Augustus R. Glasgow, Jr., Anton J. Streiff, Chas. B. Willingham & Frederick D. Rossini, *API annual meeting, Chicago, Nov 14, 46.*

Correlation of Operating Variables in the Polyform Process, Joel H. Hirsch, P. Ostergaard & W. C. Offutt, *API annual meet, Chicago, Nov 14, 46.*

Operating Characteristics of Hypercal Fractionating Columns, P. O. Brandt, R. B. Perkins, Jr., & L. K. Halverson, *API annual meeting, Chicago, Nov*

Analytical Distillation-General Principles of Definitions, C. R. Reed, *API annual meeting, Chicago, Nov 14, 46.*

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Concentric-Tube Fractionating Columns. C. K. Donnell & R. M. Kennedy, *API annual meeting, Chicago, Nov 14, 46.*

Use of a 3-In. Diameter Stedman Column for Precise Laboratory Fractionation, W. J. Borns, B. L. Coffey & L. G. Garrard, *API annual meeting, Chicag ., Nov. 14, 46.*

Fractional Analysis of Hydrocarbon Mixtures on a Gallon Scale, R. F. Marschner & W. P. Cropper, *API annual meeting, Chicago, Nov 14, 46.*

Precise Laboratory Fractionating Column, H. J. Hall, *API annual meeting, Chicago, Nov 14, 46.*

Laboratory Distilling Columns of High Efficiency Used in the Work of API Project 6, C. B. Wilingham & F. D. Rossini, *API annual meeting, Chicago, Nov 14, 46.*

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Developments in the Carbon Black Industry, Ira Williams, *API spring meeting, Amarillo, Texas, May 22-23, 47.*

Synthesis and Properties of Hydrocarbons of High Molecular Weight, Part IV, Robt. W. Schiessler, C. H. Herr, A. W. Rytina, C. A. Weisel, F. Fischl, R. L. McLaughlin & H. H. Kuehner, *API midyear meeting, St. Louis, Mo., June 2 ,47.*

Components of Gasoline, Cecil E. Boord, *API midyear meeting, St. Louis, Mo., June 2-3, 47.*

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Correlation of Accelerated and Laboratory Storage Measurements of Gasoline Stability With Field Stability, E. L. Walters, *API midyear meeting, St. Louis, Mo., June 2-3, 47.*

Application of Steam-Jet Ejectors in the Houdry Fixed-Bed Catalytic Cracking Process (In 2 Parts), Philip Freneau, Geo. Kelso & A. W. Hogue, *ASME semiannual meeting, Detroit, June 18, 46.*

Refinery Corrosion Problems, E. E. Kerns, *ASME Nat'l Conf., Tulsa, Okla., Oct 7-9, 46.*

Mechanical & Metallurgical Control of Sulphuric Acid Corrosion in Petroleum Processes, E. R. Wilkinson, *ASME Nat'l Conf, Tulsa, Oct 7-9, 46.*

Air Operated Control Instruments, V. V. Tivy, *ASME Nat'l Conf., Tulsa, Okla., Oct 7-9, 46.*

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Combustion of Coke Deposit on a Synthetic Bead Cracking Catalyst, W. A. Hagerbaumer & Russell Lee, *ASME Nat'l Conf., Tulsa, Oct 7-9, 46.*

Multi-Layer Construction of Pressure Vessels, O. R. Carpenter, *ASME Nat'l Conf., Tulsa, Okla., Oct 7-9, 46.*

Tentative Partial Enthapies of the Lighter Hydrocarbons, B. H. Sage, R. H. Olds & W. N. Lacey, *ASME Nat'l Conf., Tulsa, Okla., Oct 7-9, 46.*

Commercial TCC Operations on Partially Vaporized Charge Stocks, H. D. Noll, A. W. Hoge & D. M. Luntz, *NPA annual meeting, Atlantic City, N. J., Sept 18, 46.*

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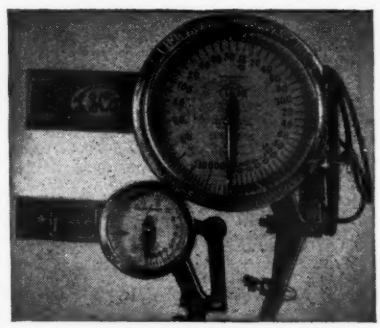

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Arsenic As a Corrosion Inhibitor in Sulfuric Acid, A. Wachter, R. S. Treseder & M. K. Weber, *NACE annual meeting, Chicago, Apr 7-10, 46.*

Phillips Cycloversion for the Smaller Refinery, M. M. Conn, *NPA semi-annual meeting, Cleveland, Ohio, Apr 17-18, 47.*

Straight Run Answers the Burning Question, J. C. Martin, C. H. Van Hartesveldt, *NPA semi-annual meeting, Cleveland, Ohio, Apr 17-18, 47.*

Effect of Temperature in TCC Catalytic Cracking, H. D. Noll, R. E. Bland & G. Kelso, *NPA semi-annual meeting, Cleveland, Ohio, Apr 17-18, 47.*

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Foreign Petroleum Refining, C. J. Bauer, *NPA semi-annual meeting, Cleveland, Ohio, Apr 17-18, 47.*

Evaluation of Sulphur Compounds in Gasoline, F. C. Moriarity, *NPA annual meeting, Atlantic City, N. J., Sept 18-20, 46.*

Concurrent Vapor Phase and Mixed Phase Operations on the Paulsboro TCC Unit, H. D. Noll, *NPA annual meet, Atlantic City, N. J., Sept. 18-20, 46.*

Octane vs. Conservation, Col. Ernest O. Thompson, *NGAA annual meeting, Dallas, Texas, Apr 17-19, 47.*

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PIPE LINE

Pipe Coatings & Corrosion Research, R. F. Hadley, *ACS regional meeting, Dallas, Texas, Dec 12-13, 46.*

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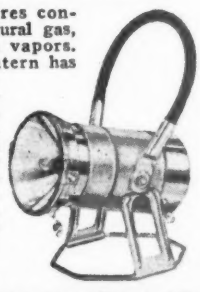

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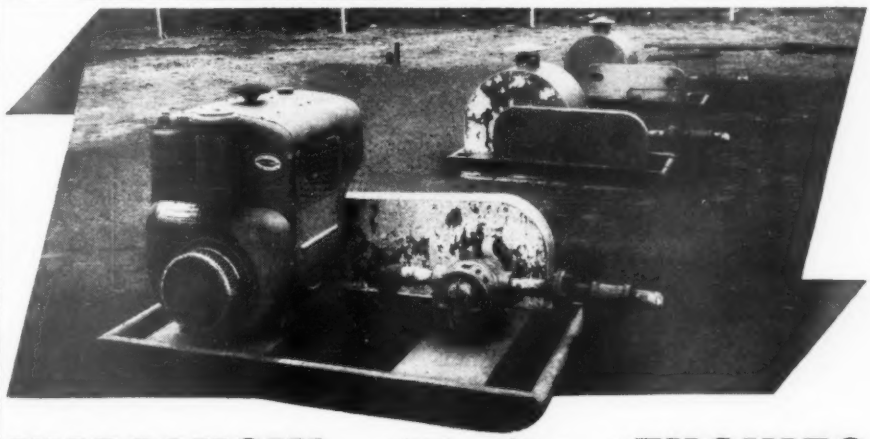

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